DATA EXTRACTABLE FROM LOGS

Aquifer properties

- depth[E]
- thickness[E]
- mineralogy[L]
- porosity[L]
- water quality (relative salinity)[open or nonmetallic casing]
- radioactivity[E]
- temperature[E]
- bulk density
- rock strength parameters
- hydraulic conductivity
- fractures
- depositional facies[E]
- moisture content in the vadose zone[E]
- confining beds[E]

Borehole characteristics

- diameter (including washouts and constrictions)
- volume
- static water level
- fluid flow (direction and velocity)[E]

Stratigraphy

- lateral and vertical extent of aquifers and confining beds[E]
- depositional facies[E]

[E] either open or cased hole
[L] limited use in cased holes
Properties with no superscript require open holes.

Well construction/well remediation

- Well construction
  - Bottom of casing
  - Partings in casing
  - Screen
- Casing integrity
  - Diameter
  - Partings & holes
  - Thickness
  - Electrical potential
- Grout
  - Top of grout
  - Channels & voids
- Gravel pack evaluation
- Fluid movement behind casing

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AN INTRODUCTION TO BOREHOLE GEOPHYSICAL LOGGING

By

Hughbert Collier

This manual is a compilation of selected notes from two short courses, **Borehole Geophysical Logging of Cased Holes** and **Fracture Detection with Borehole Geophysical Logs**, taught by Hughbert Collier for the National Ground Water Association. Therefore, the sections specifically mention fractures and cased holes. However, each section covers basic tool theory and interpretation principles, both of which apply to any application of the logging tool.

The source for all of the notes is **Borehole Geophysical Techniques for Determining the Water Quality and Reservoir Parameters of Fresh and Saline Water Aquifers in Texas**, 1993, Texas Water Development Board Report 343 (two volumes) by Hughbert Collier, which is a detailed discussion of most of the logs discussed in this introduction.

TABLE 1. OPENHOLE LOGGING TOOLS

Lithology
- SP
- Gamma Ray[1]
- Lithodensity
- Combination of porosity tools

Resistivity
- Electric
  - Single-Point Resistance
  - Normal
  - Lateral
  - Focused Electrode
  - Microlog
  - Fluid Resistivity[1]
  - Dipmeter
- Induction[2]

Porosity
- Density (Gamma Gamma)
- Dielectric[3]
- Neutron[4]
- Nuclear Magnetic Resonance
- Sonic (Acoustic)[4]

Borehole Conditions
- Borehole Deviation[1]
- Caliper[1]
- Video Camera[1]

Bedding
- Borehole Televiewer
- Formation Microscanner

Mineralogy
- Combination of porosity tools
- Geochemical
- Lithodensity

Temperature[1]

Flow Meter[1]

[1]Tool will work in cased holes.
[2]Tool will work in nonmetallic casing.
[3]Low frequency tools will work in nonmetallic casing.
[4]Tool will provide quantitative porosity data under ideal circumstances.

CASED HOLE ONLY

Casing-collar locator

Cement bond

Electrical potential

Noise

Tracers

Gravel pack

Casing inspection

CASED OR OPENHOLE

Caliper

Density

Flowmeter

Gamma ray

Induction (nonmetallic casing)

Neutron

Sonic (Acoustic)

Television

Temperature

OPENHOLE ONLY

SP

Resistivity

BOREHOLE GEOPHYSICAL LOGGING OF CASED HOLES

Geophysical logs can be run in both open and cased holes. However, if possible, it is best to log prior to running casing. Unfortunately, under certain conditions (e.g. certain drilling techniques, unstable borehole conditions) it is only possible to log the cased hole.

When planning a cased hole logging program and interpreting the logs, keep in mind the well construction:

- Casing material
  - metallic
  - nonmetallic
  - I.D.
- Screen
- Gravel pack
- Grout
  - bentonite
  - cement
  - grouting technique
- Centralizers
- Hole size

The well construction poses two obstacles for log analysis:

1. It eliminates the use of several openhole logging tools.
2. It adds another "layer" between the logging tool and the formation which affects the log response and must be factored out in order to properly interpret the formation response.

Borehole geophysical logs provide a wide range of information for groundwater/ environmental studies. They provide data for identifying and characterizing aquifers and aquitards, identifying contaminant plumes, identifying fluid movement, designing well tests, placing screens, completing wells, and evaluating well completions. Logs are used for mapping the vertical and lateral extent of aquifers and confining beds, determining depositional facies, and ground-truthing surface geophysical studies.

Some formation properties can be measured by other methods (e.g. cores, cuttings, packer tests), but wireline logging is the best or most cost effective method of acquiring these data. It has the additional advantages of being immediately available at the wellsite, providing a continuous record of the borehole, and being repeatable.

SP

The SP was one of the first logging measurements developed, yet it is still one of the most commonly run logs. The tool measures the naturally occurring potential (voltage) in the well bore.

The SP curve is used to distinguish shale from other rock types, to pick bed boundaries, to correlate, to calculate formation water resistivity (R_w), to identify permeable zones, and to calculate shale (clay) volume in sandstones. In this discussion, the terms shale and clay are used interchangeably.

SP is the only name for the tool. SP stands for **spontaneous potential** or **self potential**. On old electric logs the curve was labeled a porosity log. An SP electrode is a standard part of conventional and slimhole resistivity logging suites and is also built into many other logging tools. All SP logs are the same and are interpreted the same way.

The measurement only works in an open hole that is filled with conductive fluid. SP currents are not measured in air-filled holes and oil-based muds. As with all logs, the measurement is normally made as the tool is pulled up the borehole.

Discussions of SP interpretation in petroleum logging literature assume that the formation water is NaCl. In this discussion, explanations are given for aspects of SP analysis for which divalent ions make a difference.

Most petroleum logging literature also assumes that the formation water is more saline than the drilling fluid. However, the opposite is frequently true in water wells, which makes a significant difference in SP theory and interpretation.

Tool theory. The name spontaneous potential aptly summarizes the nature of the SP measurement. The tool sends no current into the formation; it simply measures the natural potential (voltage) difference between an electrode moving up the borehole and a stationary reference electrode. The SP has very little depth of investigation (Figure 11).

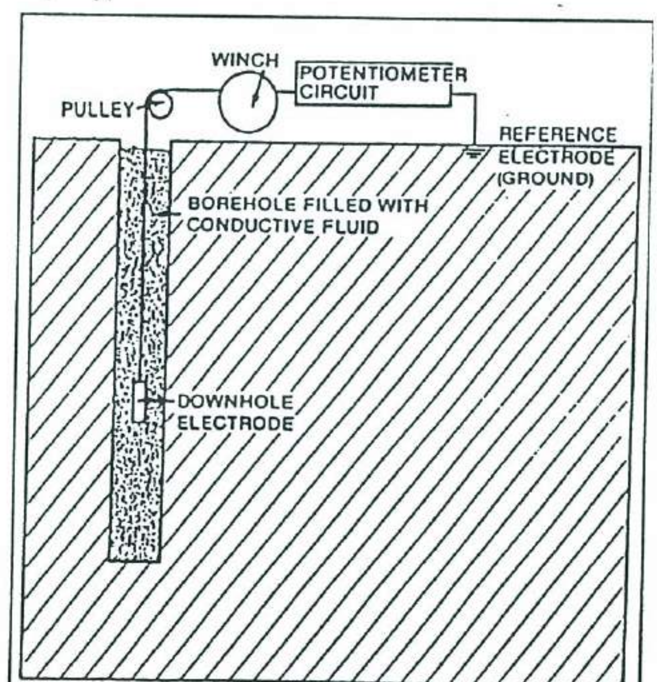


Figure 11. Schematic SP circuitry (Dresser Atlas, 1982).

The reference electrode, called a **fish**, is normally located on the surface, but it is sometimes placed on the logging cable. The electrodes are usually lead.

The SP current is generated by a combination of electrochemical (E_c) and electrokinetic (E_k) potentials. The electrokinetic potential is generally negligible; if present, it produces an abnormal SP. Normally the SP is a product of the electrochemical potential.

The **electrochemical potential** is a product of ions moving between the borehole fluid and the uninvaded formation water. This potential is only generated when there is a contrast in the ionic concentrations of the two fluids. An electrochemical potential has two components: a liquid-junction potential (E_{lj}) and a shale membrane potential (E_m).

The **shale membrane potential,** or simply **membrane potential**, is created by the flow of cations across a shale bed separating a formation water and a drilling fluid of different salinities. The negatively charged clay minerals allow cations to pass through the shale while inhibiting the movement of anions. The boundary between the shale and the less saline fluid therefore becomes positively charged and the boundary with the more saline fluid develops a negative charge (Figure 12). This creates a potential difference across the shale.

A **liquid-junction potential**, also called a **diffusion potential**, is created because cations (Na^+, Ca^{++}, Mg^{++}) and anions (Cl^-, HCO_3^-) diffuse at different speeds between two liquids (formation water and mud filtrate) of different ionic concentrations (Figure 13). Cations are less mobile because they are larger and have an affinity for the slight negative charge of water molecules. For example, at 77° F (25° C) in a NaCl solution the Cl ion is approximately 1.5 times more mobile than the Na ion (Jorden and Campbell, 1986). Therefore, at the contact or **junction** between the two waters the less saline water becomes negatively charged and the more saline water becomes positively charged (Figure 13). This induces a current flow from the less saline to the more saline water. The intensity of the current is proportional to the salinity contrast between the fluids.

The liquid-junction potential is normally one-fifth that of the shale membrane potential. The liquid-junction potential is always smaller because both cations and anions are migrating whereas in the case of the shale membrane potential only the cations migrate. Since it is the excess of one type of ion versus the other that creates the potential, the shale membrane potential is always larger (Schlumberger, 1989).

The two potentials create polarities that are opposite. When R_{mf} is greater than R_w, the liquid-junction potential creates a negative charge opposite a permeable formation while the shale membrane creates a positive charge opposite the adjacent shale (Figure 14). The result is a spontaneous current flowing between the borehole fluid, the permeable formation, and the adjacent shale. The potential only changes at the bed boundary between the permeable formation and the shale. The SP electrode detects these changes in potentials in the well bore and records them as relative

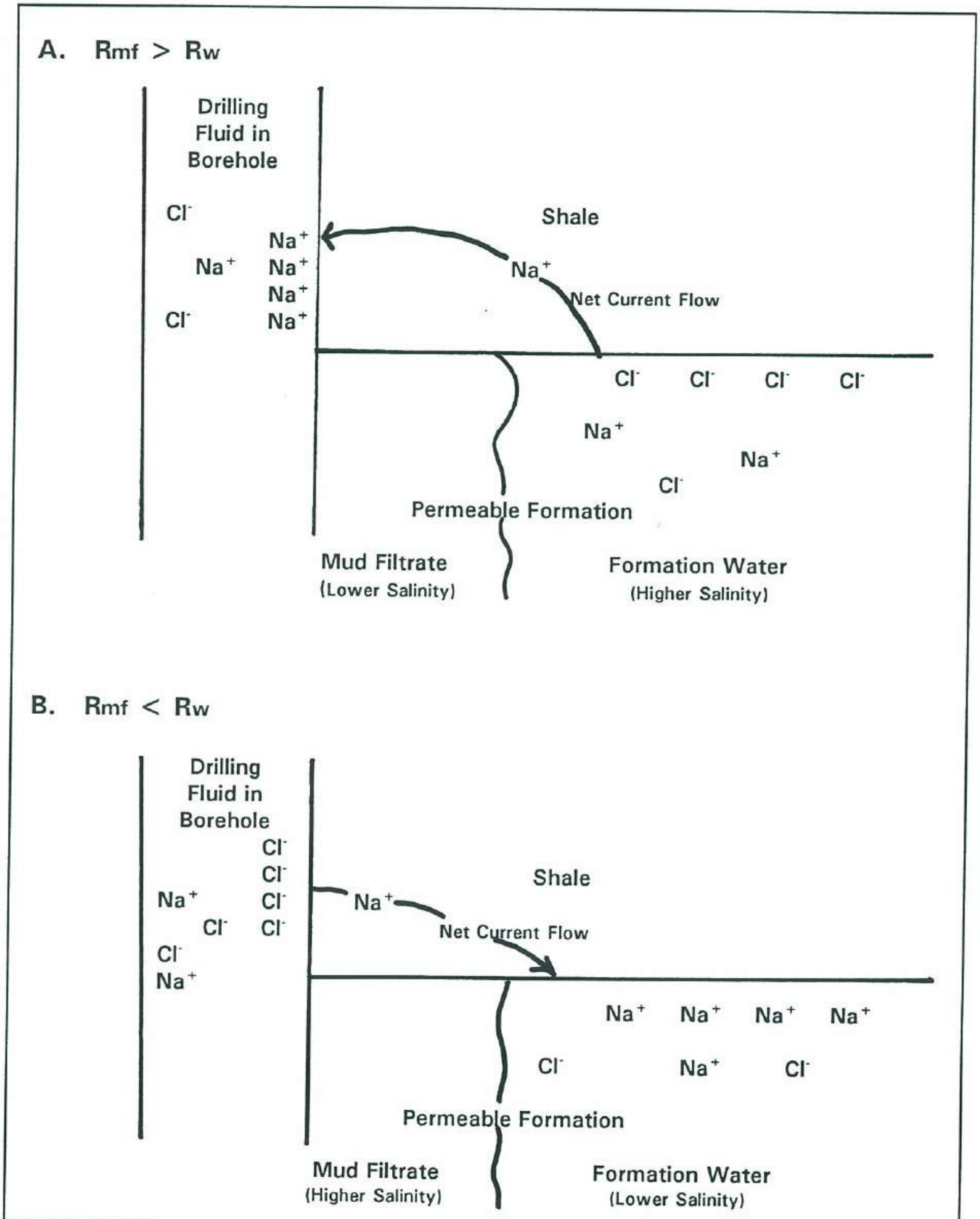


Figure 12. Shale membrane potential generated with a NaCl formation water, when R_{mf} is greater than R_w and when R_{mf} is less than R_w.

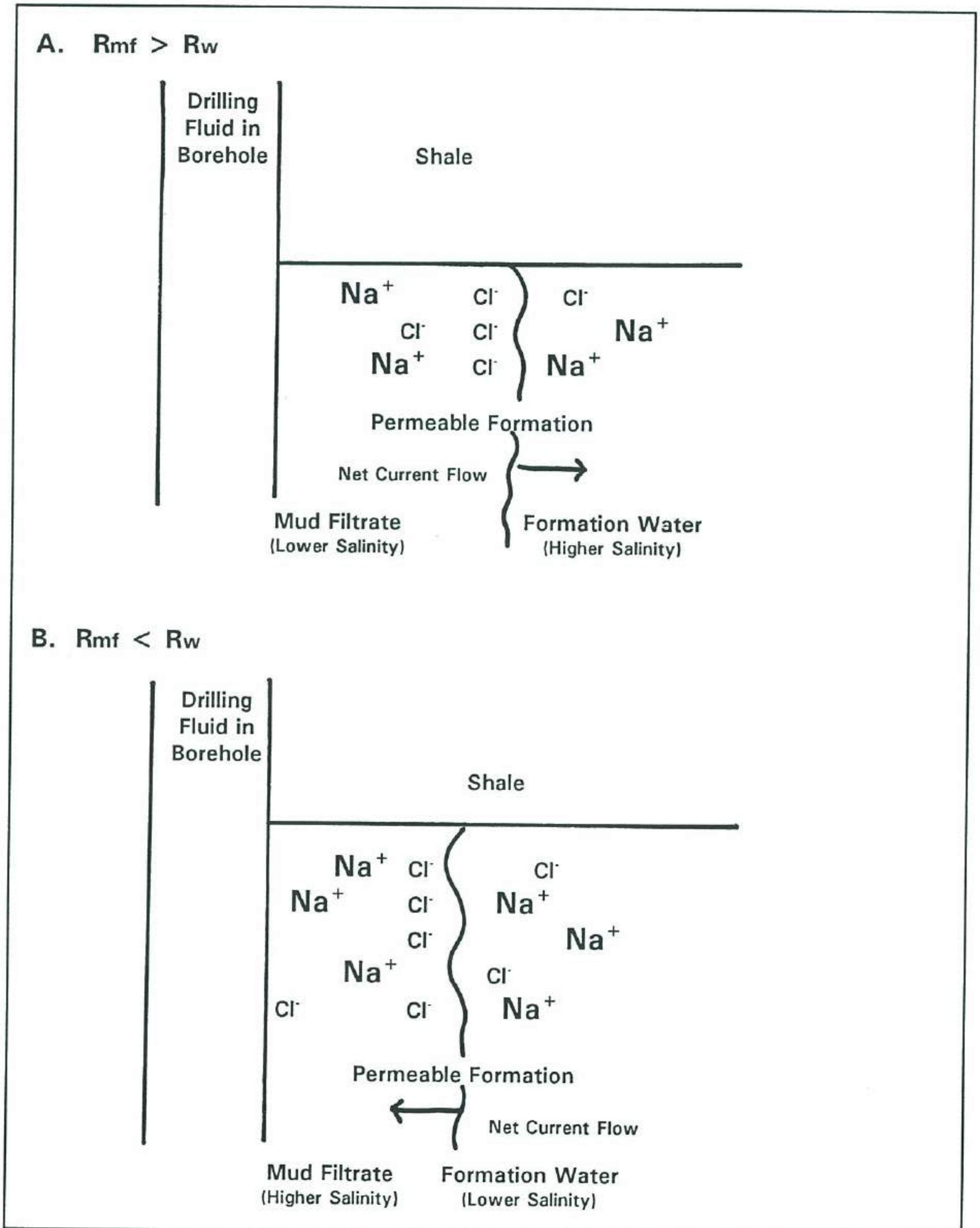


Figure 13. Liquid-junction potential generated with a NaCl formation water when R_{mf} is greater than R_w and when R_{mf} is less than R_w.

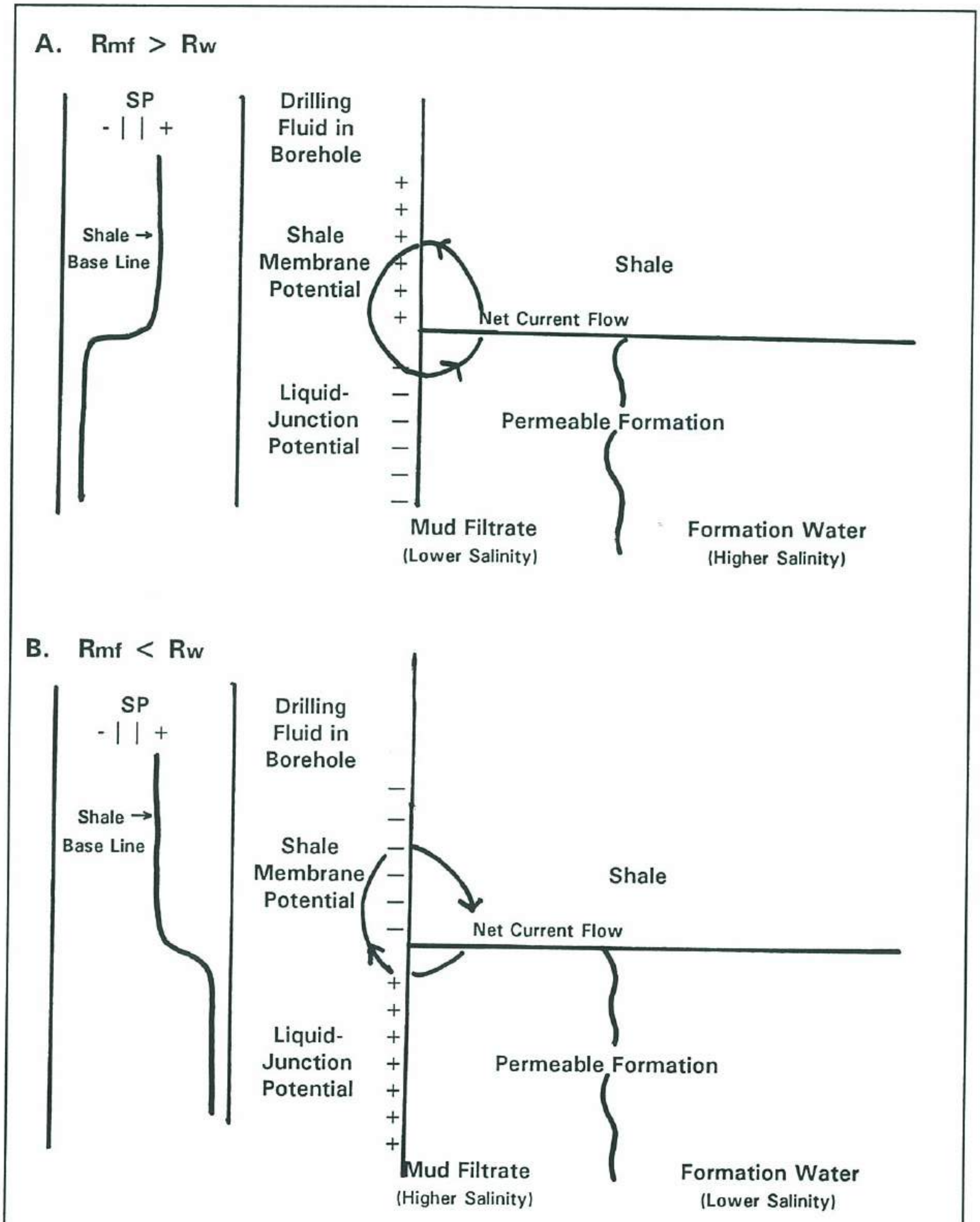


Figure 14. SP currents generated by an electrochemical potential in a NaCl formation water when $R_{mf} > R_w$ and $R_{mf} < R_w$.

negative values on the SP curve. If R_{mf} is less than R_w, the current flows in the opposite direction, the potentials are reversed, and the SP deflection is positive (Figure 14). If a formation is not permeable to ionic movement, there is no current flow, no potential change at a bed boundary, and no SP deflection.

The **electrokinetic potential**, also called the **electrofiltration** or **streaming potential**, can also create an SP current. It develops when an ionic solution flows through a nonmetallic, porous medium that has at least slight permeability (enough to permit ionic movement). The moving fluid shears the ionic double layer that exists along the pore walls of most rocks (Figure 15). This results in a net movement of cations (a current flow) in respect to the negatively charged pore walls and creates a potential difference (Jorden and Campbell, 1986).

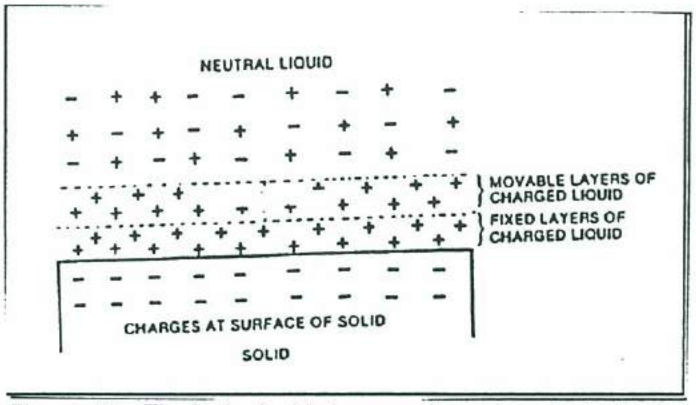


Figure 15. The ionic double layer produces an electrokinetic potential when the movable layer is sheared by fluid flow (Modified from Dresser Atlas, 1982).

An electrokinetic potential develops opposite a permeable formation as mud filtrate flows through the mudcake. Another electrokinetic potential is generated opposite shales if just a tiny amount of fluid flows into them. Both of these potentials contribute negative millivolts to the SP signal. Because they are similar in magnitude, the net effect on the SP deflection is the difference between the two potentials. This difference is usually minimal (Schlumberger, 1989).

The magnitude of the electrokinetic potential cannot be predicted with much accuracy. It is proportional to several factors: pressure differential between the borehole fluid and the formation water, resistivity of the moving fluid, rate of fluid movement, and mudcake thickness. With normal borehole conditions and a good quality drilling mud, these factors are such that the electrokinetic potential is negligible. However, under certain conditions which are more prevalent in water wells than in petroleum wells, these factors can generate a large electrokinetic potential and increase the SP by tens of millivolts.

Conditions favorable to large electrokinetic potentials include:

1. High resistivity drilling fluid and high resistivity formation water. A low salinity contrast between the two fluids minimizes the electrochemical potential, which in turn increases the relative contribution of the electrokinetic potential to the SP current.

2. Poor quality drilling mud (low viscosity, high filtrate loss).

3. Large pressure differential (several hundred psi) between the borehole fluid and the formation water. If drilling mud is flowing into the formation, either the drilling mud is abnormally heavy or the formation is underpressured. If formation water is flowing into the well bore, either the mud is too light or the formation is overpressured. In either case the pressure differential across the formation will probably be considerably different from the pressure differential across the adjacent shale. When this is the case, the two electrokinetic potentials are no longer balanced and their contribution to the SP current is enhanced.

4. Very low permeability formations (less than 5 md) that do not develop a mudcake (Serra, 1984). In this case the pressure differential is applied across the face of the formation rather than across a mudcake.

5. Relatively clay-free formations. Clay greatly reduces the electrokinetic potential (Serra, 1984).

Electrokinetic SP's may be abnormally large but at other times they are difficult to detect. Electrokinetic SP's cannot be used for quantitative calculations, but can be fracture indicators.

For the situations listed above, if the mud filtrate is fresh, even the very slow movement of fluid into a formation creates a large negative SP deflection. If formation water is moving into the borehole, the result can be a large positive deflection.

Log presentation. The SP curve is placed in track 1. It is almost always found on the resistivity log, and it is sometimes placed on the porosity log. The SP scale is in + or - millivolts (mv). The curve has no absolute values. Zero is defined as the SP value opposite thick shales, the **shale base line** (Figure 16). SP deflections to the left of the shale base line are - SP's and those to the right are +. The magnitude of these deflections is measured relative to the shale base line (Figure 16). Slimhole tools are scaled the same way, but the curve is not always in track 1.

The curve is scaled with large enough millivolt units to eliminate backup curves and yet the units are kept as small as possible to maximize resolution. On petroleum logs the number of millivolts per division is normally a multiple of 5, anywhere from 5 to 20. Groundwater logs where R_{mf} and R_w are very similar and the curve is very flat may use an expanded scale such as 2 millivolts per division to enhance the resolution.

On older conventional logs and on slimhole logs the scale is designated as -|**10**|+, which designates the number of millivolts per each of the 10 divisions in track 1. Modern conventional logs use a different label **(-80.00 SP (MV) 20.00)** to represent the same scale. This scale does not assign any specific value (-50 mv, -40 mv, etc.) to a particular division -- all specific values are still determined in reference to the shale base line.

On conventional logs the engineer normally places the shale base line about two divisions from the right side of track 1. As the tool is pulled up the hole the curve often drifts (Figure 16). To keep the curve from drifting out of track 1 the engineer may have to shift the curve. Any manual shifts should be done rapidly over a vertical interval of only a few feet and should be so labeled on the log. Some engineers slowly adjust ("knob") the SP during the course of a logging run. This creates havoc with quantitative SP analysis and is a poor practice. It cannot be detected on the log.

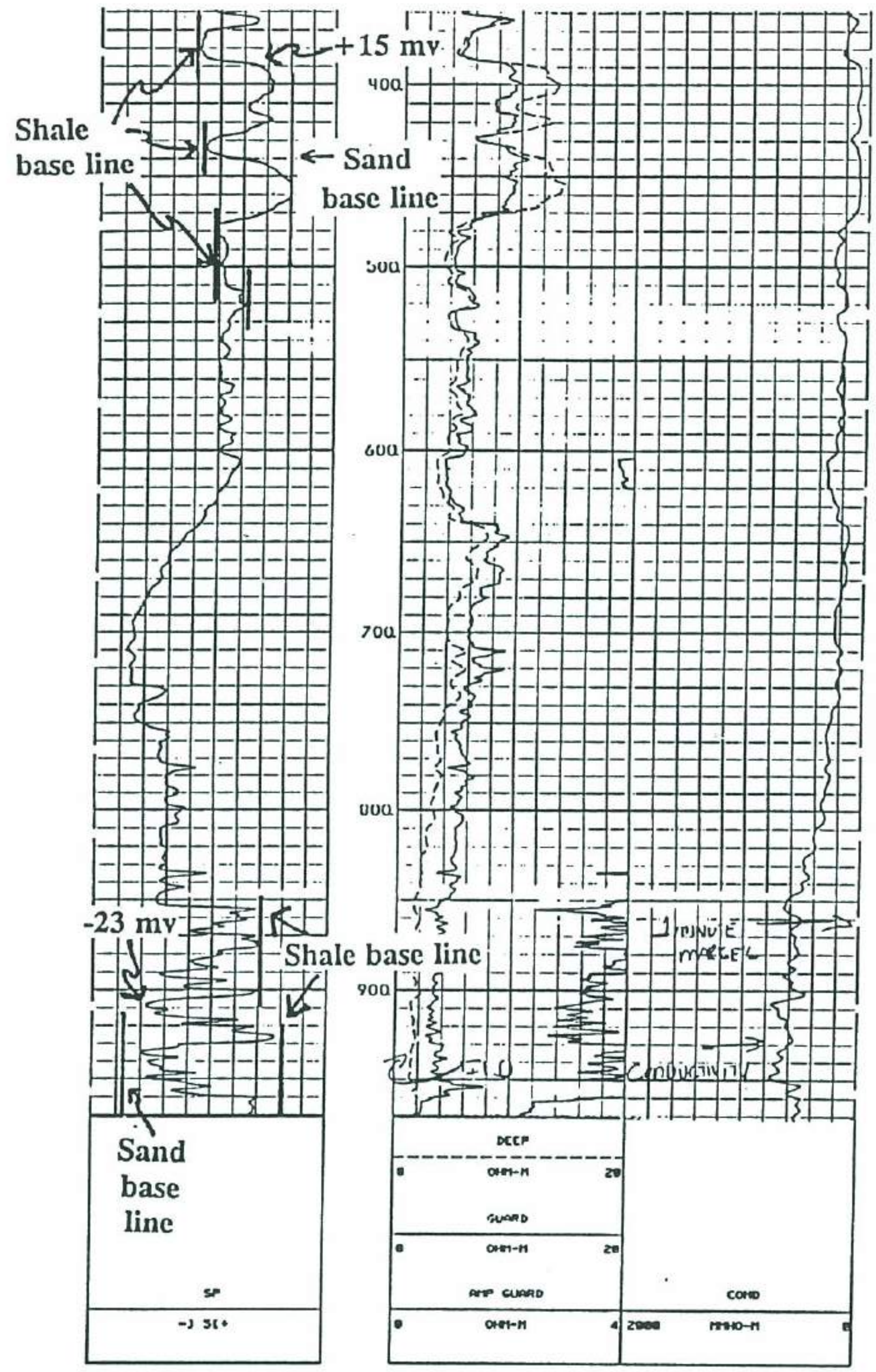


Figure 16. Typical SP curve presentation. The shale base line is drifting to the left as depth decreases. The abnormal SP from 690 to 610 feet may be where the logging engineer slowly moved the SP curve to the right in order to keep it from running off the left side of track 1. An alternate explanation is that the drift is due to water salinity in the formations changing up the well bore from saline to fresh. Above 550 feet the sands have positive SP deflections because R_w is greater than R_{mf} (as confirmed by the deep induction curve reading higher than the shallow guard curve). Below 800 feet the sands all have negative SP deflections because R_w is now less than R_{mf} (as confirmed by the reversal in the resistivity curves). A positive and a negative SP value have been picked on the log.

RESISTIVITY TOOLS

Nonfocused Electrode Tool

Mandrel

- Single-point
- Normal
- Lateral

Pad (Microelectrode)

- Microlog

Focused Electrode Tools

Mandrel

- Guard
- Point-electrode
- Shallow investigating
- Spherically focusing
- Dual Focusing

Pad (Microelectrode)

- Microlaterolog
- Proximity
- Microspherically focusing

Induction

Dual Induction

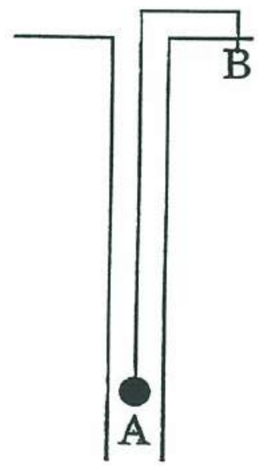
SINGLE - POINT

AC current travels from A to B.

A serves as both current and potential electrode.

Measures resistance (ohms).

Curve is strictly qualitative.



SINGLE-POINT RESISTANCE

Single-point resistance tools are also known as single-point, point-resistance, or single-electrode tools. The tool was rarely used in the petroleum industry. Only slimhole single-points are available today. They are used extensively in groundwater, coal, uranium, and environmental site assessment logging.

Tool theory. The single-point is the simplest type of "resistivity" tool. The tool actually measures resistance rather than resistivity. Resistance is a function of both resistivity and the geometry of the material being measured. The relationship between resistance and resistivity can be illustrated in terms of a copper wire. The wire has a specific electrical resistance for a given volume, meter^2 per meter, which is its resistivity. It is an inherent physical property of the wire which does not change in value. The resistance of the wire to the flow of an electrical current is a function of both its inherent resistivity and the length of the wire (geometry of the material). Resistance changes as the geometry of the wire changes. A long wire has a high resistance while a short wire has a very low resistance.

There are two types of tools: conventional and differential. The conventional single-point system consists of a surface and a downhole electrode. The differential system has both electrodes downhole; the return electrode is the probe housing. Both tools measure the potential difference between the two electrodes in volts. The potential difference between the two is proportional to resistance, thus allowing resistance to be measured.

The length of the electrode (2 to 3 inches) determines the depth of investigation and the vertical resolution. The depth of investigation for 50 percent of the signal is twice the electrode length. The vertical resolution is equal to or greater than the electrode length. The differential single-point has better vertical resolution than the conventional tool (Keys, 1988).

Not much literature exists on the single point. Guyod (1944) has an excellent discussion of the tool. Keys (1988) gives a detailed discussion of the tool theory for both the conventional and the differential single-point systems.

Log presentation. Both conventional and differential tools measure the resistance in ohms of the material lying between the two electrodes. The log curve is a solid line and is scaled in ohms per inch (Keys, 1988).

Interpretation. The single-point has a few strengths and several weaknesses.

Strengths.

1. The electrode configuration gives excellent thin bed resolution (2 to 3 inches, depending on the length of the electrode).

2. The tool is able to detect fluid-filled fractures. The differential system is more sensitive to narrow fractures than is the conventional system (Howard, 1990).

3. The curve is symmetrical. The tool configuration eliminates distorted curve shapes such as are common to normal and lateral curves.

4. Measurements can be made to the bottom of the borehole and right up to either metallic casing or fluid level (Guyod, 1944).

Weaknesses.

1. The shallow depth of investigation means that the current path is dominated by the borehole fluid and borehole diameter. The tool is adversely affected by large boreholes and high R_{xo}/R_m values.

    a. For boreholes much larger than 5 inches, the tool is primarily measuring the resistance of the borehole fluid.

    b. When the flushed zone resistivity is greater than the borehole fluid resistivity (R_{xo}/R_m greater than 1), which is usually the case in ground-water aquifers, the tool measures far less than true resistivity.

2. The severity of the borehole effect, plus the nonlinear curve response, means that no confidence can be placed in the resistance values. The curve is strictly qualitative, showing nothing more than relative changes in resistivity.

3. As with all nonfocused electrode tools, the single-point is adversely affected by any type of stray electrical currents (e.g. grounding problems, powerlines, etc.).

4. Low resistance anomalies can be caused by lithologic changes and washouts, as well as by fractures. Other logs must be used to support the fracture interpretation.

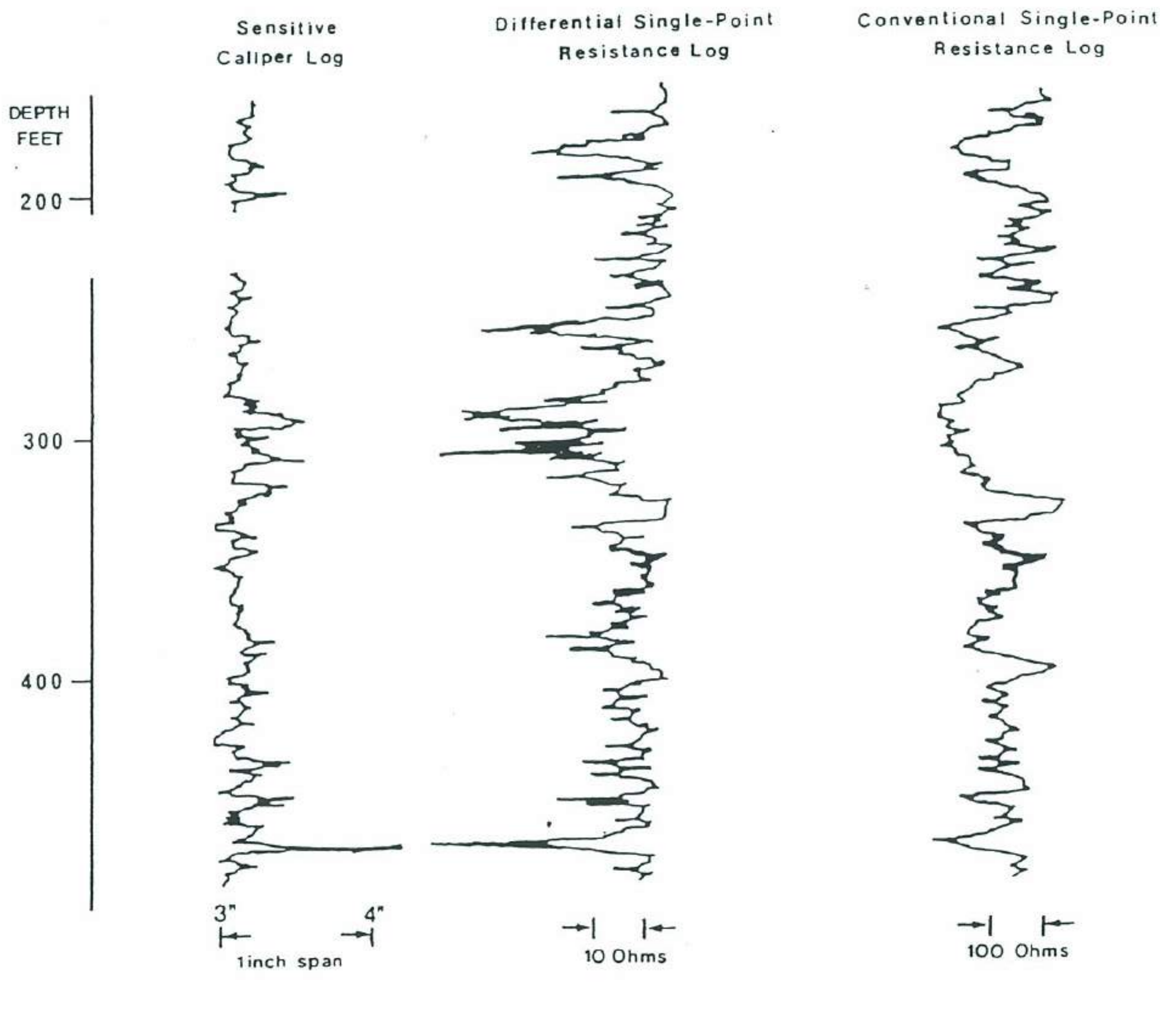


Figure A. A comparison of conventional and differential single point resistance logs with a caliper log. The logs were run in crystalline rock (Keys and MacCary, 1971, Howard, 1990).

NORMAL

A is current electrode.

Voltage between M & N measured.

K(V/I) = Resistivity (ohms)

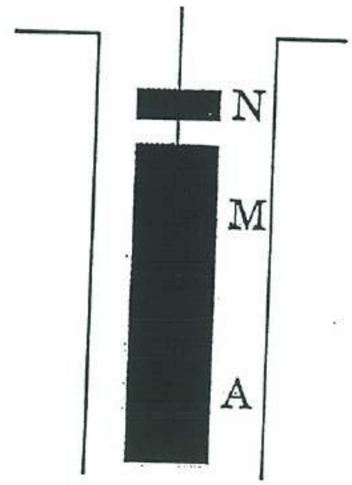
Electrode spacing (AM) varies.

8", **16"**, 32", **64"**

Measures Ri or Rt.

Depth of investigation = 2 AM

Vertical resolution $\propto$ AM



NORMAL

The normal tool was introduced in 1931. Normal curves were an integral part of every resistivity logging suite until the 1950's when they were replaced by induction and laterolog tools. Today they are the mainstay of groundwater and environmental slimhole resistivity logging suites. In fact, slimhole logging companies are the only ones still running the tools.

There are no trade names for the normal tool. The logging suite consisting of a short normal, long normal, lateral, and SP was variously called an Electrical Survey (ES), an Electric Log (EL) or an E log.

Tool theory. The normal tool is also called the two-electrode tool. In practice, three electrodes are downhole as illustrated in Figure 1. The N electrode is the bare cable armor. Between N and the normal device, a distance of 10 to 20 feet, the cable is wrapped with insulating tape. The electrodes can be arranged so that N is on the surface, which makes the tool a true two-electrode tool.

The tool measures the voltage (V_{mea}) between electrodes M and N. R_a is calculated from the equation $K(V_{mea}/I) = R_a$. K is a constant which is dependent on the electrode configuration. I is the survey current.

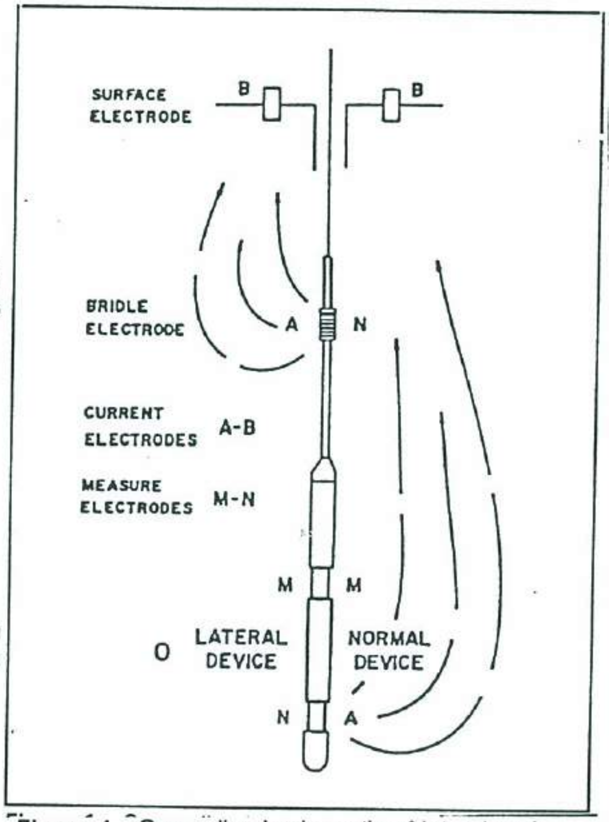


Figure 1. Generalized schematic of lateral and normal tools. A constant survey current flows from electrode A to electrode B (From Labo, 1986).

The position of the N electrode determines how close to fluid level and to metallic casing the tool can log. If N is on the surface, the tool can log right up to either. If, however, N is the cable armor, the tool can only log to within an AN spacing of either.

Through the years the electrode spacing (initially designated as AM∞, but standardized as AM) has ranged from 8" to 84". Halliburton's 18 inch spacing was designated as 2Z 18". Many slimhole tools offer four spacings (8", 16", 32", and 64"). Only two of the spacings can be run at one time. The most popular AM spacings are a 16" short normal for R_i and a 64" long normal for R_t.

Depth of investigation increases as the electrode spacing increases. For normal tools the depth of investigation in isotropic, homogenous formations is equal to or less than 2AM. This means that a short normal will have good vertical resolution, but the tradeoff is a shallow depth of investigation which makes for a significant R_{xo} influence on the curve.

Log presentation. The curves are presented in either track 2 or tracks 2 and 3. The short normal is always a solid curve. The long normal is usually dashed. However, some slimhole logs also have the long normal as a solid line.

Electrode spacing. The ratio of the AM spacing to bed thickness has considerable effect on curve response, especially for resistive beds. Figures 2 and 3 illustrate the curve responses for resistive and conductive beds of varying thicknesses. Resistive beds are by definition beds that have a higher R_t than the adjacent or shoulder beds. Conductive beds have a lower R_t than adjacent beds. Figure 4 illustrates the curve response in highly resistive formations.

Interpretation. Normal curves should be interpreted according to the following guidelines:

1. Resistivity values are picked at the point of maximum deflection.

2. Normal curves are symmetrical in resistive beds that have less than about 200 ohm-meters (Douglas Hilchie, personal communication, 1986) and in conductive beds.

3. Bed boundaries are not sharp because the tool is averaging a sample volume equal to the diameter of the AM spacing.

4. Resistive beds appear thinner than they are by an AM spacing (½AM spacing at the top and ½AM spacing at the bottom). Refer to Figure 2.

5. For resistive beds, the accuracy of R_a varies with bed thickness. Refer to Figure 2.

   a. Beds thicker than 4AM record the true resistivity value.
   b. For beds between 4AM and 1.5AM in thickness, as bed thickness decreases, so does the resistivity value
   c. Beds thinner than 1.5AM "disappear" and appear to be conductive beds. Horns appear above and below the bed.

6. Conductive beds appear thicker than they are by an AM spacing (½AM spacing at the top and ½AM spacing at the bottom). Refer to Figure 3.

7. The thinner a conductive bed is, the higher the log resistivity. However, it always appears as a conductive bed no matter how thin it becomes. Refer to Figure 3.

8. Above about 200 ohm-meters (Hilchie, personal communication, 1986) resistive beds take on asymmetrical triangular curve shapes. Refer to Figure 4. The peak is displaced upward toward an adjacent conductive bed. It occurs a distance of AN below the upper resistive bed boundary. The curve is asymmetrical because the tool has three electrodes downhole. If two electrodes are used downhole, the curve maintains a symmetrical shape at high resistivities (Schlumberger, 1987).

9. In a low resistivity formation at the bottom of the hole, the curve will read too high and in a high resistivity formation at the bottom of the hole it will read too low (Pirson, 1963).

10. In thinly bedded sequences of varying resistivities (e.g. sand-shale or porous-nonporous carbonate sequences) the adjacent beds begin to influence each other's log values and greatly complicate the curve shapes. In order to interpret these curve shapes, Guyod (1958) did extensive modeling of normal curve shapes using analog models. His report is not easy to obtain because few copies were printed and it was only published as an in-house report. However, Hilchie (1979) has included a brief summary of Guyod's analog models that is detailed enough for most work.

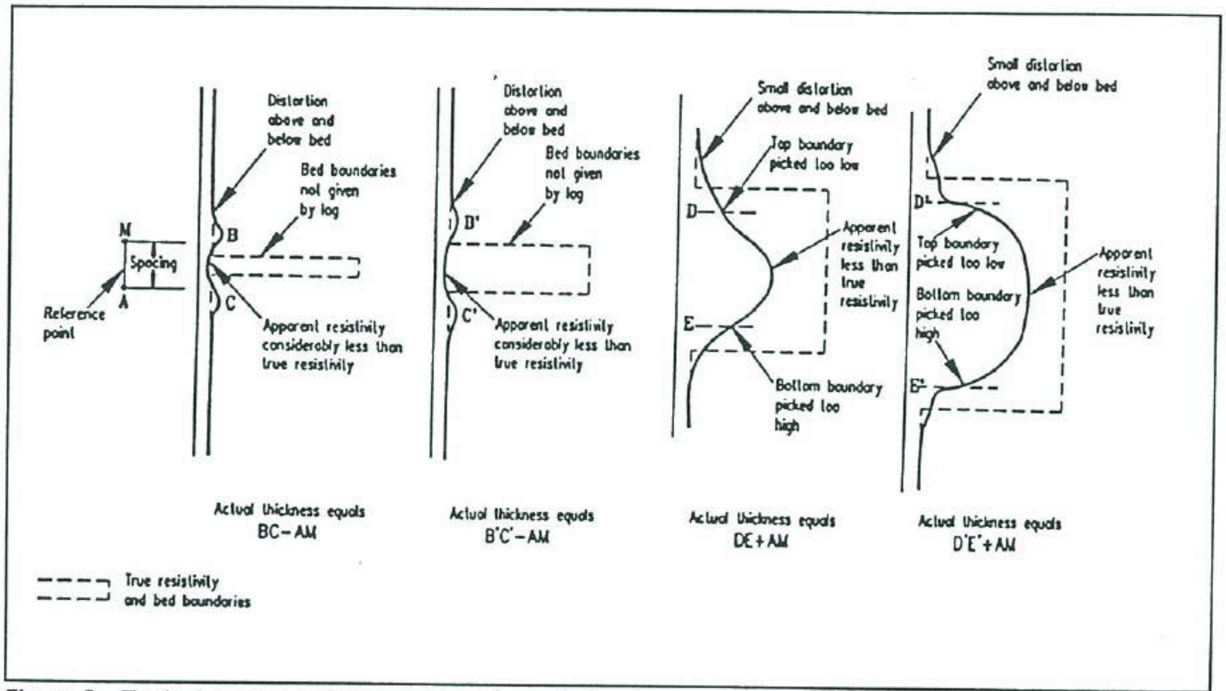


Figure 2. Typical normal curve responses for resistive beds of varying thicknesses (Modified from Guyod, 1944).

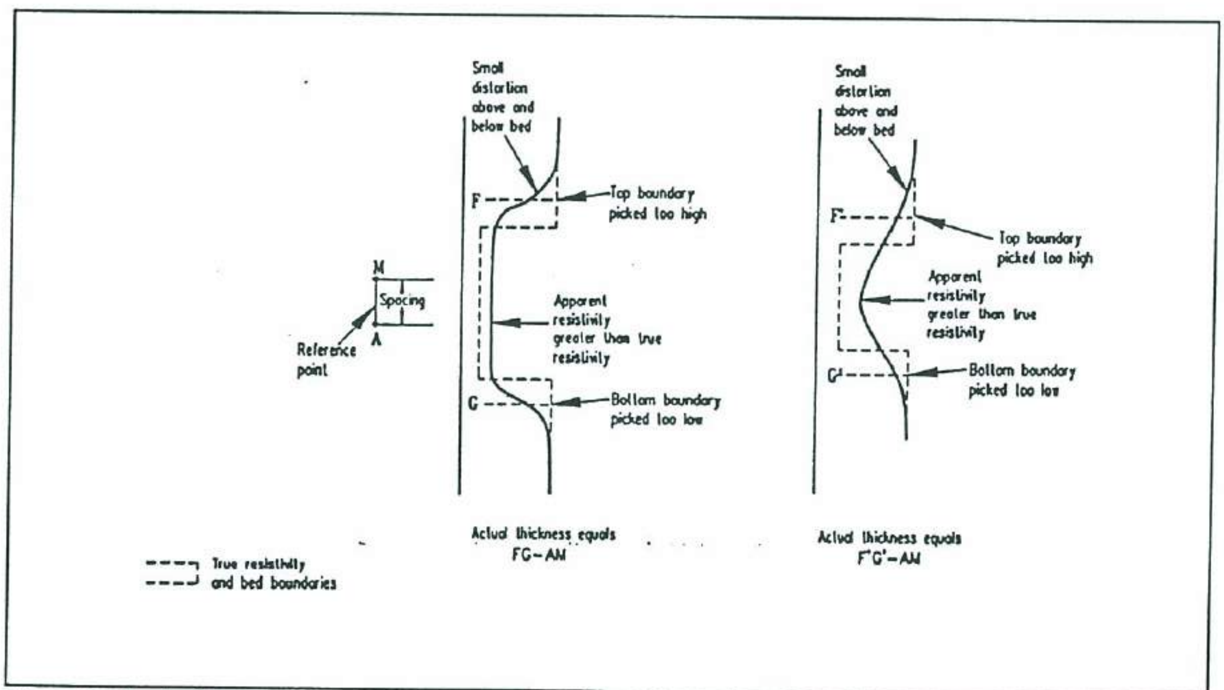


Figure 3. Typical normal curve responses for conductive beds of varying thicknesses (Modified from Guyod, 1944).

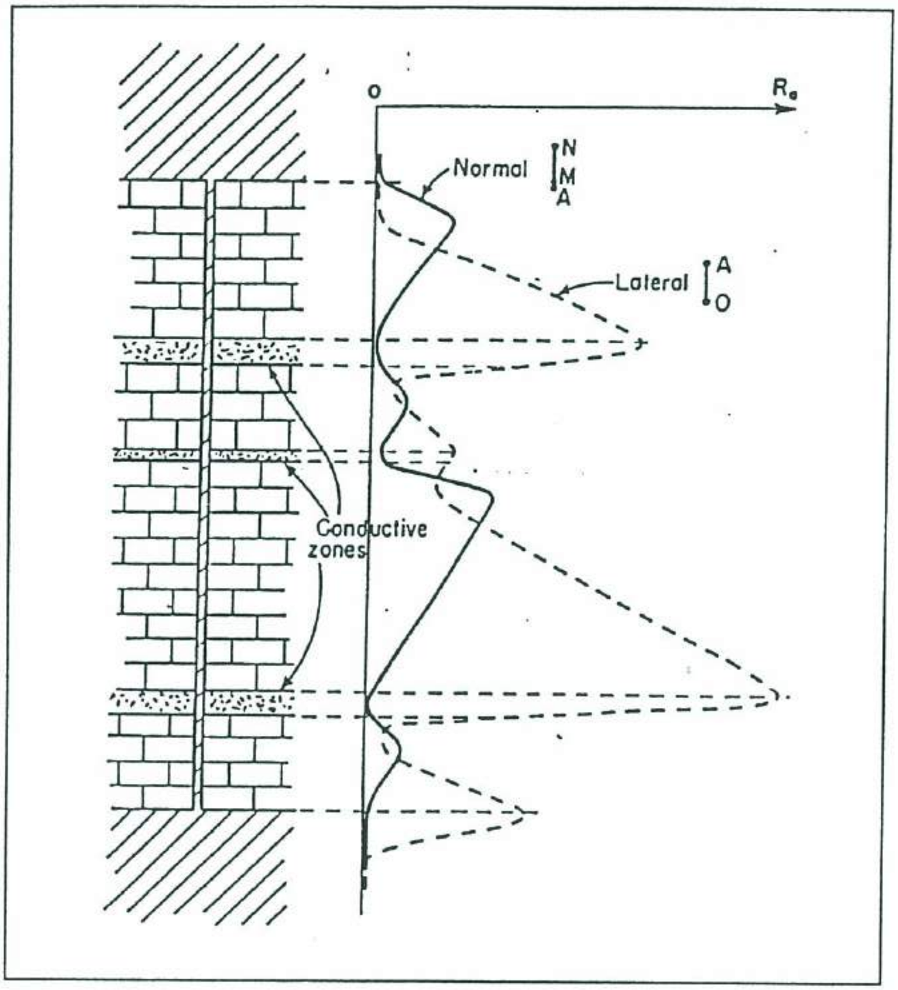


Figure 4. Normal and lateral curves take on asymmetrical triangular curve shapes in highly resistive formations. AMN and AO are the electrode spacings (From Schlumberger, 1949).

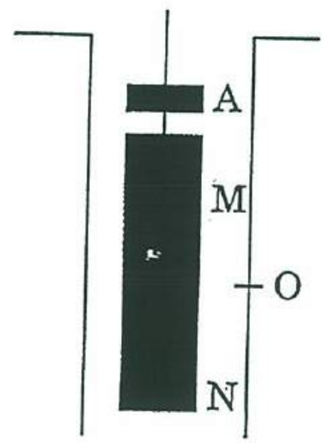
Fractures. Normal and lateral logs detect steeply dipping to vertical fractures better than horizontal fractures; the 16 inch normal is more sensitive to fractures that the 64 inch. Fractures are best detected in low porosity (i.e. high resistivity) rocks, since fluid-filled fractures provide a significant resistivity contrast with the host rock. The lower the resistivity of the fluid in the fractures, whether it be drilling fluid or natural fluid, the greater the contrast. Fractures in high porosity rock will not be detectable with resistivity logs because they do not significantly lower the resistivity.

LATERAL

A is current electrode.

Voltage between M and N measured.

$$K(V/I) = R$$



Electrode spacing AO varies.

6' – 18'8"

Measures Rt.

Depth of investigation = AO

Vertical resolution ∝ AO

LATERAL

The first log ever run was a lateral or three-electrode curve (Hilchie, 1979). Until the 1950's, resistivity logging suites were a combination of lateral and normal curves. Today a 6 foot slimhole lateral is run by a few groundwater logging companies. The tool has no trade name.

Tool theory. Tool theory is summarized in Figure 1. The electrode spacing (AO) ranges from 5 to 24 feet, but 18'8" became the predominate spacing in the petroleum industry. Halliburton designated their electrode spacing 3iZ.

Depth of investigation equals the electrode spacing. A long tool spacing gives the lateral the greatest depth of investigation of any nonfocused electrode tool. The tool usually measures R_t.

Log presentation. The standard oilfield presentation in Texas was a solid lateral curve in track 3. The presentation varied in other parts of the country. Curve response is complicated in thick beds (Figures 5 and 6).

Fractures. See the discussion of normal logs.

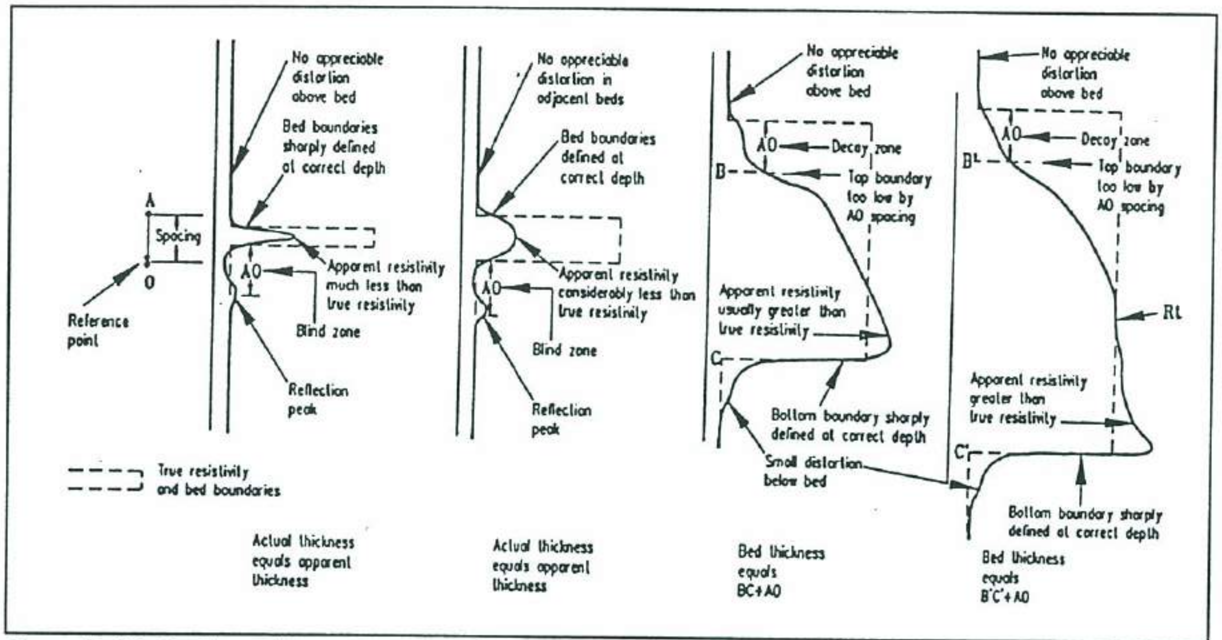


Figure 5. Typical lateral curve responses for resistive beds of varying thicknesses (Modified from Guyod, 1944).

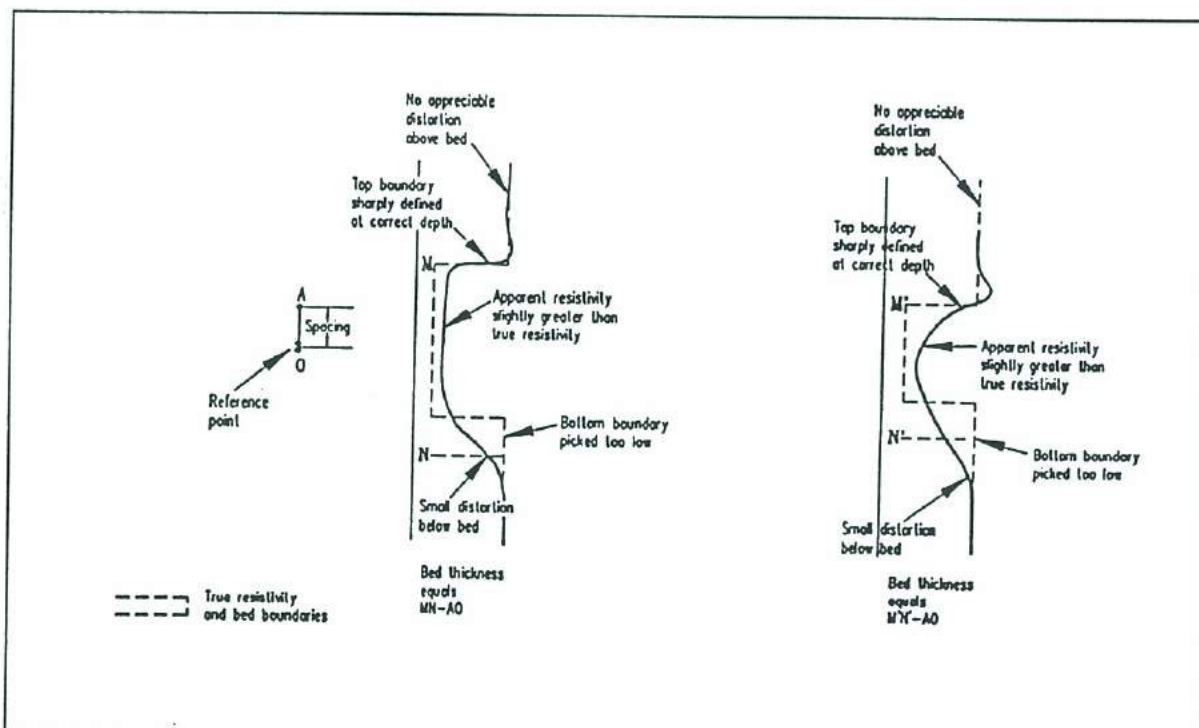


Figure 6. Typical lateral curves for conductive beds of varying thicknesses (Modified from Guyod, 1944).

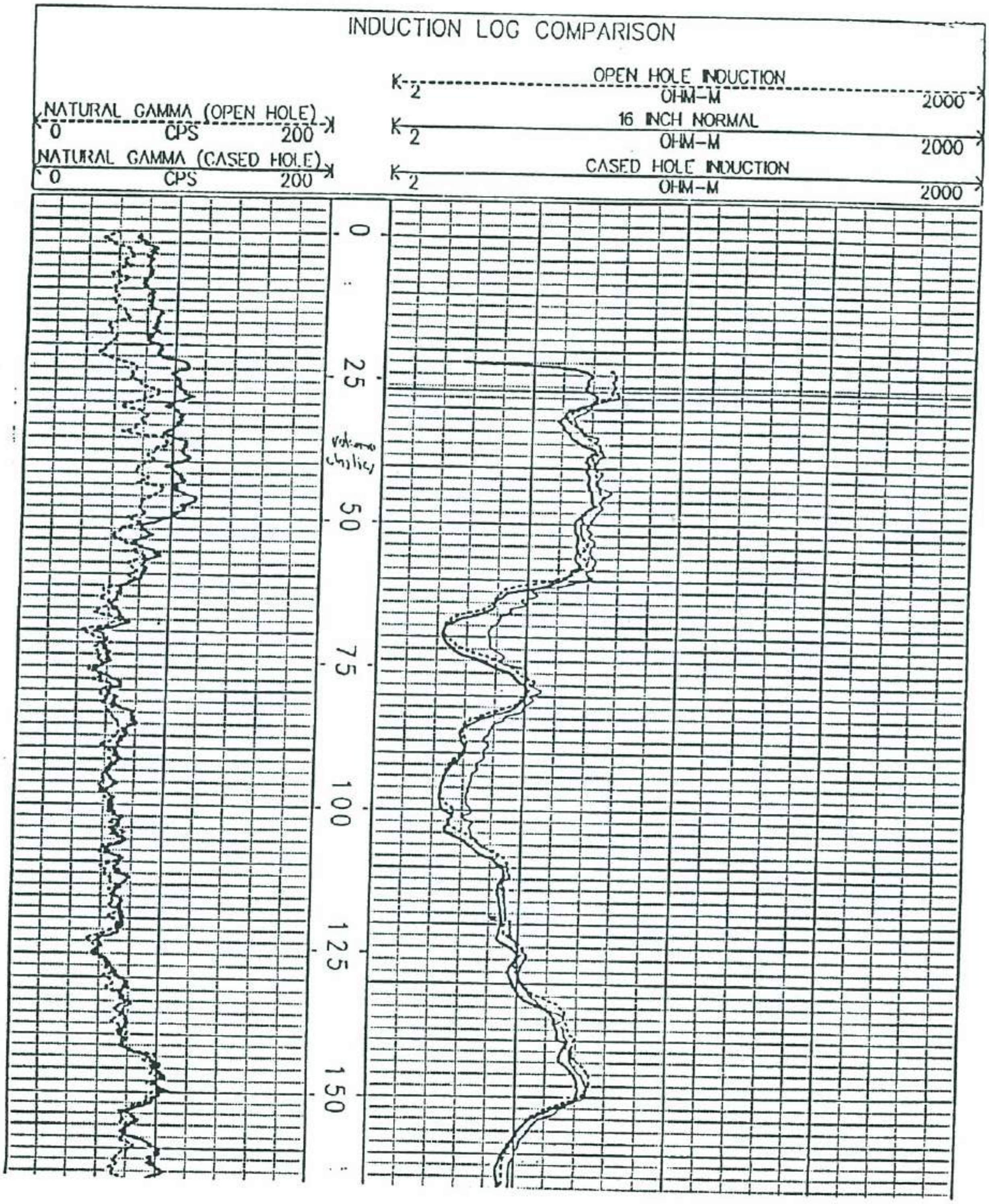
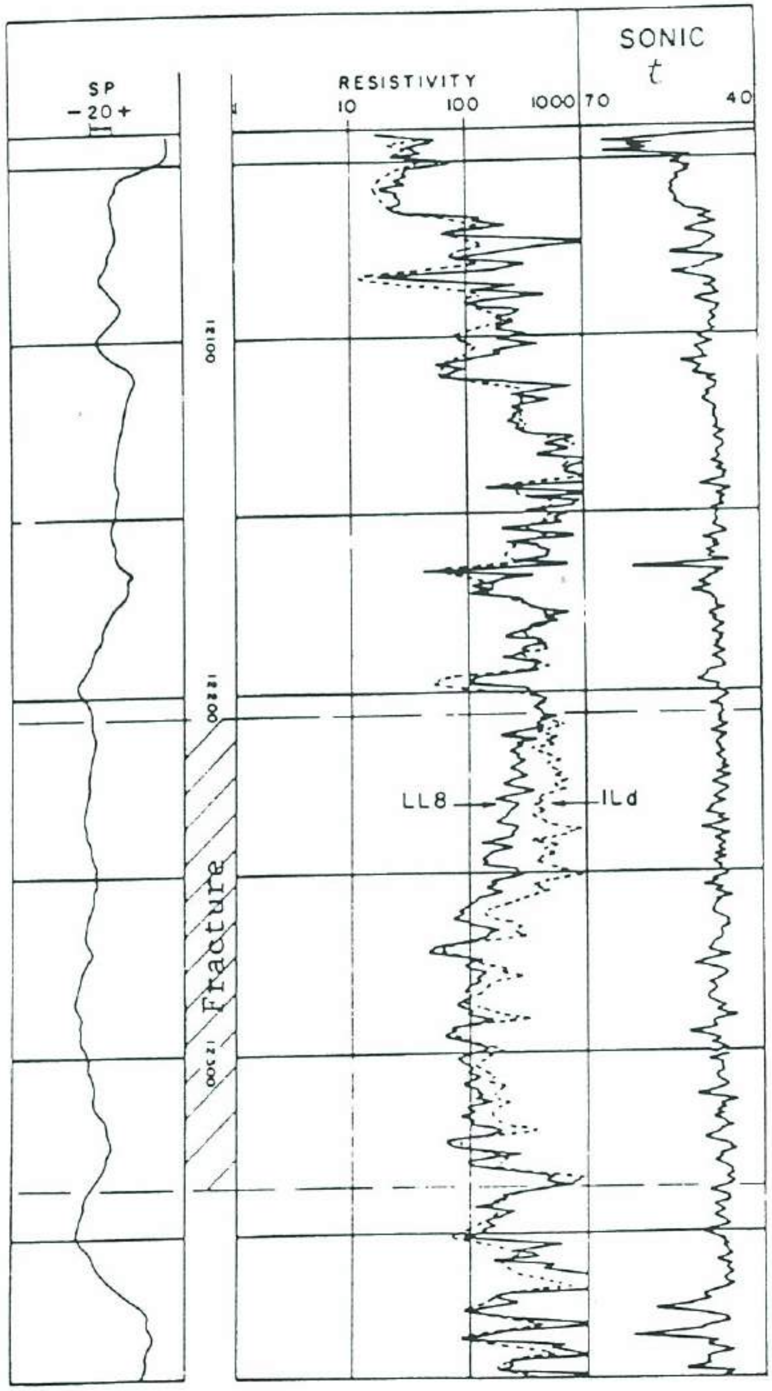


Figure 9-24. Comparison of a slimhole induction tool in a borehole (open and cased). The tool has excellent repeatability in the nonmetallic casing. The open hole diameter is 9 inches. The cased hole is 4 inch PVC and is grouted with 5 percent bentonite cement. The open and cased hole gamma rays also have excellent repeatability. The lithology is volcaniclastics. The well is in Colorado. The nature of the borehole fluid is not known.

Figure 10-4 An example of a long vertical fracture detected by a laterolog and induction log.



(Tixier et al - courtesy SPE of AIME)

(Hilchie, 1987)

INDUCTION

Induction tools were introduced in the 1950's. The tool was developed for boreholes with nonconductive fluids (oil-based mud, air, or foam). It is the only resistivity tool that will work in nonconductive borehole fluid and in nonmetallic casing. (No resistivity tool works in steel casing.) Today in the petroleum industry it is the most commonly run resistivity log. The array induction is a new improved version.

Slimhole tools are available and are becoming more common in the groundwater industry. Robertson Geologging, Geonics, and Century Geophysical manufacture induction tools that are less than 2 inches in diameter.

Tool theory. Induction tools induce a current in the formation. A high-frequency alternating current in a transmitter coil creates an alternating electromagnetic field in the formation. The alternating magnetic field induces Foucault currents in the surrounding formation. These currents flow in horizontal ground loops in the formation. The currents create a magnetic field in the formation which induces a voltage in a receiver coil. The induced voltage is proportional to the formation conductivity (C), which is the reciprocal of resistivity ($R_{ohm\text{-}meters} = 1000/C_{mmhos/m}$).

The more sophisticated induction tools employ a number of coils, which serves to focus the signal. A focused tool has better vertical resolution, increased depth of investigation, minimized adjacent bed effects, and minimized borehole effects.

Vertical resolution is about 3 feet for the medium induction and 4 to 5 feet for the deep induction. The array induction has a vertical resolution of 1 foot. Depth of investigation is greater than 5 feet for the deep induction and about 3 feet for the medium.

Log presentation. Induction curves are always in tracks 2 and/or 3. The curves are displayed as resistivity. The only time that conductivity values appear on the log is on a 2 inch linear scale where the deep induction conductivity is in track 3. The conductivity values can be used as a quality control check of the log. The deep induction curve is long dashes, the medium induction curve is short dashes, and the shallow reading curve such as the SFL or Guard is a solid line).

GAMMA RAY

The gamma ray tool measures the natural radioactivity of formations. The log is used to distinguish shale and clay from other rock types, to pick bed boundaries, to correlate, and to calculate shale volume in sandstones and carbonates (Figure 1). In this discussion shale and clay are used interchangeably.

The tool may be used in open or cased holes. It is usually run in combination with other tools. **Gamma ray** is the only name for the tool. A variety of slimhole and conventional tools are available.

Tool theory. The gamma ray tool is basically just a gamma ray detector. Most conventional tools use a scintillation counter which consists of a sodium iodide crystal and a photomultiplier tube. Each gamma ray that strikes the crystal produces a light flash. The light flashes are converted to electrical pulses by the photomultiplier and multiplied into a voltage that can be counted. The tool records the number of pulses per unit of time.

Modern conventional tools and a few slimhole tools are scaled in API (American Petroleum

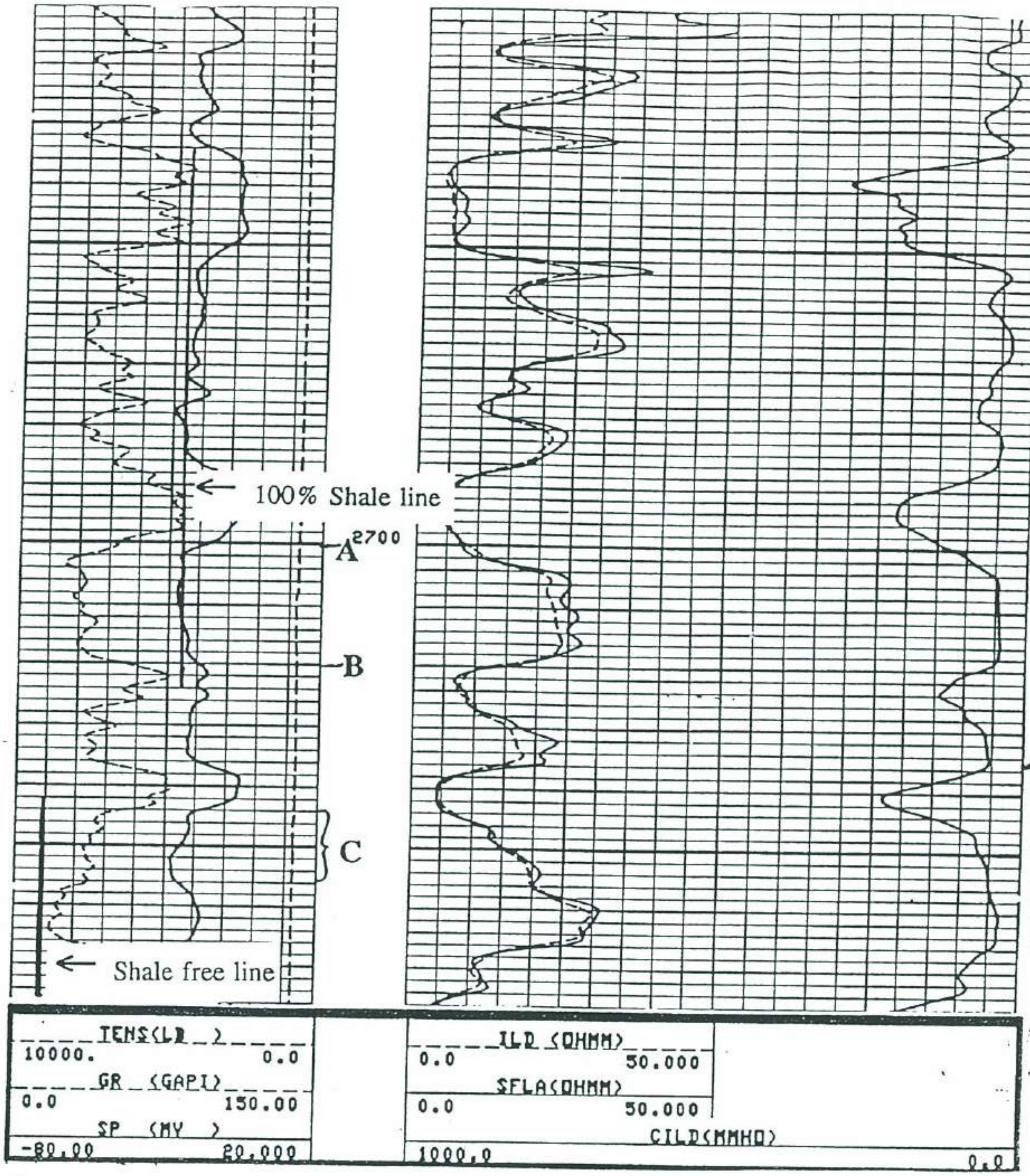


Figure 1. This log shows a typical gamma ray presentation. The gamma ray and SP curves are both scaled so that shale-free formations are to the left and shale content increases to the right. The SP and gamma ray curves correlate well, with the gamma ray having the best bed resolution. Bed boundaries are picked on the gamma ray curve half way between the high and low values. For example, point A at 2700 feet and point B at 2720 feet are the bed boundaries for a sandstone. The 100 percent shale line and the shale-free line have been drawn on the log. The shale content of zone C is approximately 24 percent. The bit size is 9⅞ inches and the mud is 9 lb/gal fresh water bentonite.

Institute) units. An API unit is defined as $^1/_{200}$ of the response generated by a calibration standard at the University of Houston. The standard is composed of known amounts of uranium, potassium, and thorium. It was designed to have twice the gamma ray response of an average shale, which is considered to be 6 ppm (parts per million) uranium, 12 ppm thorium, and 2 percent by weight potassium (Dewan, 1983). Thus most shales measure about 100 API units.

Depth of investigation and vertical resolution. The vertical resolution of gamma ray tools with scintillation counters is about 3 feet (Dewan, 1983). Vertical resolution is a function of logging speed, detector length, and time constant. The depth of investigation, 6 to 12 inches, is a function of the penetrating power of gamma rays and the formation density. Depth of investigation increases as formation density decreases (i.e. as porosity increases). The effect of formation density on the gamma ray count is not significant for gamma ray tools.

Log presentation. The gamma ray curve is placed in track 1 on conventional logs (Figure 1). The curve is linear and is usually scaled from 0 to 100 API units or 0 to 150 API units, depending on the radioactivity level of the shales in the well bore. Increasing radioactivity is to the right, thus the curve mimics the SP curve.

Slimhole tools are often scaled in counts per second and there is little consistency to the log presentation. A few companies use API units.

Interpretation. Gamma rays are high-energy electromagnetic waves that are emitted naturally from the nuclei of certain radioactive elements. They are most commonly emitted by elements of the uranium-radium series, the thorium series, and potassium-40, a radioactive isotope of potassium that occurs in association with normal potassium. These elements may either be an allogenic (primary) constituent of the rock as part of the chemical composition of the minerals or they may be an authigenic (secondary) product, which is absorbed onto the surface of the mineral. In sedimentary rocks, shales and clays, both of which are referred to as shale in this text, have by far the highest concentrations of these elements, while rocks such as sandstones and carbonates usually have very little. This means that the tool can be used to distinguish shale from nonshale and to calculate the percentage of shale in nonshale formations. This is why many people refer to the gamma ray curve as a lithology log.

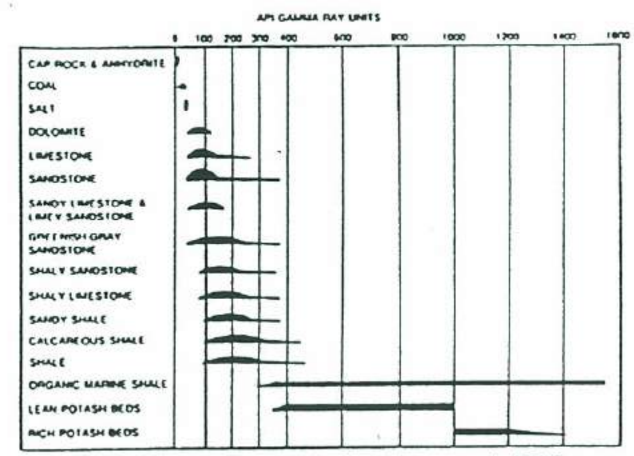
Figure 2 lists the API units of various types of sedimentary rocks. In general gypsum, anhydrite, halite, and coal have the lowest API readings. Carbonates are a little higher and sandstones still a little higher (20-30 API units). Shales or clays are much higher, around 100 API units. The radioactivity of a rock increases as the organic content increases due to the affinity between organic matter and uranium and thorium. While it is true that shales generally have much higher gamma ray counts than other sedimentary rocks, there are important exceptions. Each lithology has a range of gamma ray radioactivity rather than a discrete value. Therefore, interpretation of a gamma ray curve is not always straighforward.

High gamma ray counts do not always correspond to shale. Both feldspathic sandstones (arkose, granite wash) and micaceous sandstones have high gamma ray counts due to high potassium concentrations. Glauconite, heavy minerals, volcanic ash, and uranium salts also give high gamma ray counts and can occur in both carbonates and sandstones.

Conversely, **low gamma ray counts do not always mean that a formation is shale free.** Kaolinite and chlorite are two common clay minerals that have low radioactivity levels and are indistinguishable from sandstones and carbonates. These clays are nonradioactive because they do not contain potassium and they adsorb very few uranium ions due to very low cation exchange capacities, which is the tendency of some clays to absorb cations to fill unsatisfied electrical charges. Of the common clay minerals only smectite (montmorillonite) and illite have a high API value. These two clays do have significant radioactivity because illite contains potassium and both clays have an appreciable cation exchange capacity (CEC).

Acidic and intermediate igneous rocks (those with potassium feldspar) such as granite and rhyolite and metamorphic rocks have even higher radioactivities than shales. Any formation with an appreciable amount of these rock fragments will appear to be a shale. Basic igneous rocks (e.g. basalt and gabbro) have very low radioactivities. Some evaporites, principally potash minerals, contain high potassium concentrations and are very radioactive. Potassium rich pegmatites have a high gamma ray count.

The gamma ray tool works very well in cased holes. It can be accurately interpreted by following a few guidelines. Steel casing reduces the gamma ray activity by about 30 percent (Helander, 1983). PVC casing only slightly reduces the gamma ray count. Cement, which contains clay, may increase or decrease the gamma ray count depending on the radioactivity of the formation relative to the cement. Bentonite grout will significantly increase the gamma ray count. Cased holes with a few inches of a fairly uniform thickness of grout or cement will produce an overall shift in the gamma ray response, but shale/nonshale bed boundaries will still be discernible. However, the gamma ray curve will mask the formation response if the cement or the grout is abnormally thick. If the cement or the grout varies greatly in thickness up and down the well bore, the curve can be misleading.



The length of the line denotes the intensity range in API Gamma Ray Units. The vertical width of the line increases with the frequency of occurrence.

Figure 2. Gamma ray log response in API units of common sedimentary rocks (From Dresser Atlas, 1982).

SPECTRAL GAMMA RAY

The spectral gamma ray tool also measures the natural radioactivity of formations. In addition to measuring the total gamma ray activity, the tool measures the energy level of each gamma ray and calculates the concentrations of uranium, thorium, and potassium.

Spectral gamma ray is a generic name for the tool. Each logging company has its trade name for the tool: Spectralog or SGR (Atlas Wireline), Natural Gamma Ray Spectral Log or SGR (Gearhart), Compensated Spectral Natural Gamma Ray or CSNG (Welex and Halliburton Logging Services), and Natural Gamma Ray Spectrometry Log or NGS (Schlumberger). A few slimhole tools are also available.

DENSITY (GAMMA-GAMMA)

The density or gamma-gamma tool is an excellent porosity tool. It is also used to pick bed boundaries. In conjunction with other porosity tools it can be used to determine lithology. It is used in conjunction with the sonic log to calculate acoustic impedance for synthetic seismic traces and to calculate formation mechanical properties such as Poisson's ratio and Young's modulus. While it is predominately an openhole tool, research is being conducted into methods of obtaining quantitative data through metallic casing (Jacobson and Fu, 1990). Density tools are used to detect voids in gravel packs in cased holes. Attempts have been made to evaluate the distribution of bentonite grout behind PVC casing utilizing slimhole density tools (Yearsley, et al., 1991).

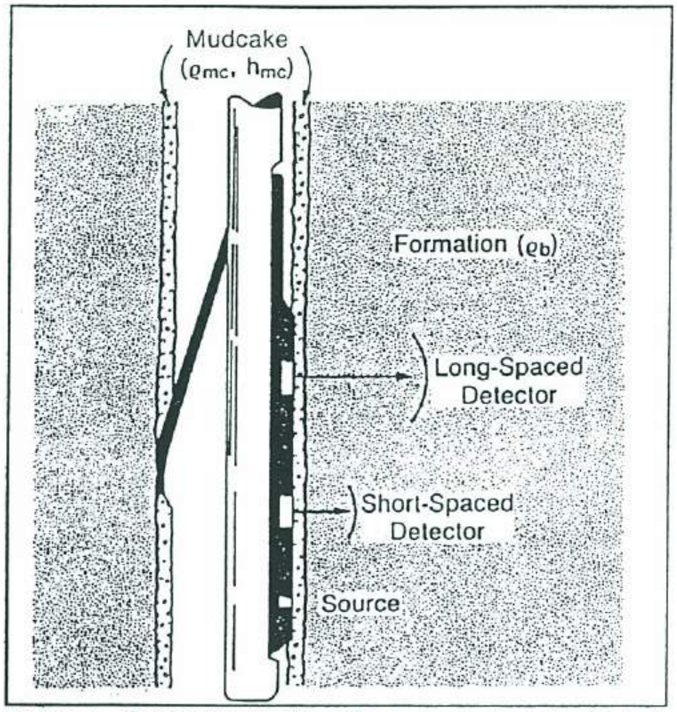


Figure 3. Schematic drawing of a compensated density tool (From Schlumberger, 1989, modified from Wahl, et al., 1964).

In some parts of the country the tool cannot be run in openhole water wells. The concern is that the radioactive source would create very localized radioactive contamination if the tool should become stuck in the borehole.

The most common name for modern conventional tools is Compensated Density (CDL). Atlas Wireline uses the name Compensated Densilog (CDL); Schlumberger calls its tool the Compensated Formation Density (FDC). Slimhole tools are called either density or gamma-gamma and the term compensated is added when appropriate.

Tool theory. Conventional and some slimhole density tools utilize a source which emits medium-energy gamma rays (Cobalt 60 or Cesium 137) and which is mounted in a shielded sidewall skid. The skid is pressed against the borehole wall by means of an eccentering arm that also functions as a caliper (Figure 3). The pressure of the eccentering arm, plus the plow-shaped design of the leading edge of the skid, usually allows the skid to cut through the mudcake.

The tool design creates collimated (focused) gamma rays that pass into the formation. As the gamma rays pass through the formation several reactions take place. Compton scattering is the only reaction of consequence to most density tools. It occurs when gamma rays lose energy and change direction due to collisions with electrons in the rock and fluid.

Density tools measure the attenuation of gamma rays between the source and one or two detectors. The detectors emit an electrical pulse for each gamma ray that is intercepted. The count rate varies by a factor of 5 to 10 for common sedimentary rocks (Dewan, 1983). The detectors are shielded in such a way that they respond only to the gamma rays undergoing Compton scattering. Such shielding makes the count rate a function of the electron density.

The gamma ray count measured by the detector(s) is inversely proportional to the electron density (ϱ_e) of the formation. Electron density, in turn, is proportional to the bulk density (ϱ_b) of the formation. For common sedimentary rocks the ratio of ϱ_e to ϱ_b varies very little. This means that it is a relatively easy, accurate, and straightforward process to convert the gamma ray count to bulk density. Conventional and some slimhole density tools output bulk density as the "raw" data curve.

There is considerable variation in the design of slimhole density tools. Some tools are compensated (dual detectors), but many are single detector. The single detector tools include omnidirectional, mandrel tools as well as sidewall tools. Omnidirectional density tools are commonly called 4-pi density tools. The name alludes to the fact that the tool investigates a spherical area, the volume of which is $4\Pi r^3/3$. The Greek letter Π is pi. The tool may or may not be centralized. Uses include gravel pack evaluation and delineation of thin beds in coal sequences (personal communication, Lynn Gray Breaux, 1991).

Depth of investigation and vertical resolution. Depth of investigation is only a few inches, with 5 inches a good average value.

This shallow depth of investigation makes the tool response very susceptible to the influence of borehole conditions such as excessive hole rugosity and thick mudcake. Porosity values are too high when such conditions exist. Drilling methods (such as augering) that disturb the formation for just a few inches away from the well bore will adversely affect the ability of the tool to measure true bulk density.

Vertical resolution of conventional tools is about 3 feet at average logging speeds (30 feet per minute). Slowing the logging speed to about 15 feet per minute improves the statistics, thus increasing the vertical resolution to 1.5 feet. Petroleum logging companies offer high resolution density logs with a vertical resolution of 0.5 feet. The improved resolution of this tool is accomplished by combining a slower logging speed and an increased sampling rate with a different processing technique.

Vertical resolution is also a function of the source-to-detector(s) or the detector-to-detector spacing. The smaller the spacing the better the vertical resolution. While the spacing varies somewhat for each brand of density tool, average values are 16 inches for single detector conventional tools and 10 inches between detectors for compensated conventional tools (Serra, 1984). Slimhole tools usually have spacings that are a few inches smaller. Good vertical resolution makes the density log useful for determining bed boundaries.

Log presentation. Density logs vary considerably in their presentation. They may consist of one to seven curves, but the common format is five curves: bulk density, porosity, correction, caliper, and tension.

Conventional and some slimhole density tools record bulk density as the "raw" data curve, but some logs include count rate curves. The bulk density curve is labeled RHOB on the header, which is computer keyboard phonetics for ϱ_b. The unit of measurement is grams per cubic centimeter (g/cm^3). The curve is usually placed across tracks 2 and 3 with a linear scale of 2.0 g/cm^3 to 3.0 g/cm^3. This scale covers the range of values occurring in common sedimentary rocks with less than 46 percent porosity.

The output of many slimhole tools is simply the count rate of each detector scaled in counts per second. For many of these logs no further processing is or can be done to the data. Compensated density tools correct the bulk density curve for the presence of mudcake not removed by the leading edge of the sonde and for washouts and borehole rugosity by comparing the differences in the count rates of the two detectors by means of an experimentally derived "spine-and-ribs" plot. The correction is automatically added to the bulk density curve, making it in actuality a corrected bulk density curve. The amount of correction is documented on the log as a separate curve labeled $\Delta\varrho$ (**DRHO**). The curve is usually placed in track 3 with a scale of -0.25 g/cm^3 to 0.25 g/cm3.

Monitoring Well Completion Evaluation with Borehole Geophysical Density Logging

by E.N. Yearsley, R.E. Crowder, and L.A. Irons

Abstract

Grout continuity and the location of the bentonite seal and sand pack in PVC-cased monitoring wells can be evaluated with cased-hole geophysical density logs. This method relies upon density contrasts among various completion conditions and annular materials. Notably, the lack of annular material behind pipe (i.e., void space) creates a low-density zone that is readily detected by borehole density measurements.

Acoustic cement bond logging has typically been applied to the evaluation of cement in the annular space of completed oil and gas production wells, and in some cases to ground water monitoring wells. These logs, however, can only be obtained in the fluid-filled portion of the borehole, and their interpretation is severely hindered by the presence of the micro-annulus between casing and cement. The influence of the micro-annulus on cement bond logs can be mitigated in steel-cased wells by pressurizing the wellbore during acquisition of the log, but this procedure is not feasible in PVC-cased monitoring wells. The micro-annulus does not affect cased-hole density logs or their interpretation.

Empirical measurements made in the laboratory with density probes provide information on their depths of investigation and response to specific completion conditions. These empirical data, and general knowledge of the density of annular completion materials (sand, bentonite, cement), are used to support interpretations of cased-hole density logs acquired in the field. Three field examples demonstrate the applicability of geophysical density logs to the evaluation of PVC-cased monitoring well completions.

Introduction

In recent years there has been an emerging realization among ground water professionals, environmental contractors, and regulators that in some cases the installation of monitoring wells has contributed to the transport of contaminants by providing a vertical path for flow in the annular space of completed wells. Although completion practices in potentially hazardous environments are designed to eliminate leakage through the annular space by filling this space with an annular seal (cement, bentonite, or a mixture of the two), the potential for voids and channels in the annular material is significant.

The common method for emplacement of annular material in monitoring wells is the use of a tremie pipe through which the material is gravity fed or pumped down the annulus, usually from the bottom up. Because the drilled borehole often contains cavities or washouts and the annular space is not pressurized during emplacement of the annular materials, voids or channels in the annular space are common. The "ideal" well completion may differ from the actual case, resulting in the potential for cross contamination (Figure 1).

Currently, no reliable method exists to evaluate the presence or continuity of annular materials in PVC-cased monitoring wells (Aller et al. 1989). In some cases, acoustic cement bond logging has been applied to this problem, but this method is severely limited in PVC-cased wells, as discussed in the next section.

However, cased-hole geophysical density logging may provide a method by which the presence and continuity of the annular seal material can be reliably assessed. The principle of this approach is based on the density contrasts among various completion conditions. The lack of completion material behind pipe (i.e., void), for example, creates a low-density zone that is readily detected by borehole density measurements. Furthermore, the densities of certain annular completion materials (sand, bentonite, cement) are often sufficiently different to be distinguished behind pipe, so it is possible that their location may be verified by density measurements. Knowledge of the densities of completion materials and the geologic media in which the monitoring wells are drilled is imperative to the interpretation of cased-hole density logs in recognizing specific completion conditions. Table 1 lists approximate densities of some commonly used completion materials and average densities of selected geologic media.

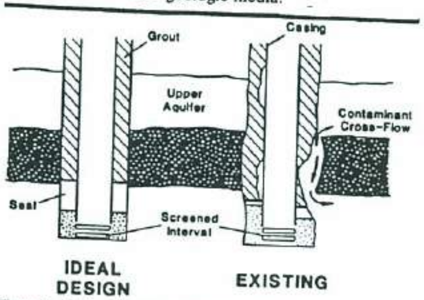


Figure 1. Ideal completion design vs. possible existing scenario for a ground water monitoring well.

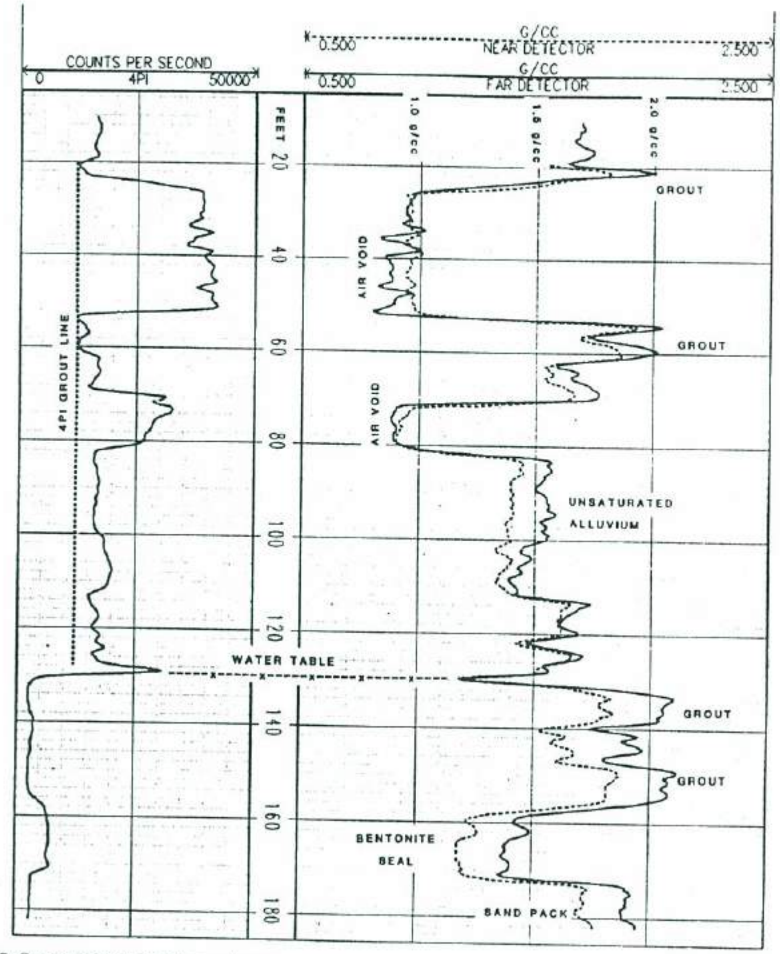


Figure 7. Geophysical logs for field example one.

saturated sand pack and dry sand pack. The presence of the seal is questionable, because it is not known if the seal is saturated (its design location is above the water table). Grout is indicated by comparatively high densities (higher than unsaturated alluvium) below the design depth of the seal, which suggests that at least part of the seal is missing, because the grout is typically installed after the seal.

A major air void is distinctly recognized by near and far detector measurements below 1.0 g/cc, values supported by data contained in Table 2. The remainder of the interval above the water table consists of mostly alluvium, with only limited grout zones and a section of gravel pack near the surface. The 4Pi log identifies the major air void and water level in the borehole (which can be different than the water table in the formation, but in examples 1 and 2 are the same), and supports the interpretations made from the focused density log concerning the lack of grout above the water table (see the 4Pi grout line). Therefore, this second example also illustrates that vertical cross-flow along the outside of pipe is possible, and the completion goal of isolating the monitored zone is probably not achieved.

The last field example, shown in Figure 10, is a

A caliper curve is standard on most density logs. The backup arm of the sonde makes the caliper measurement. The curve is usually placed in track 1.

Neutron

The neutron tool is used to calculate porosity and pick bed boundaries. It can also be used to delineate water-saturated zones. In conjunction with another porosity tool, usually the density, it can be used to determine lithology. Certain neutron tools can be used in air-filled holes and in cased holes.

Most service companies call their modern, coventional tool a Compensated Neutron. However, each company uses a different abbreviation for the tool: Schlumberger (CNL), Atlas Wireline (CN), and Gearhart (CNS). Halliburton calls its tool a Dual Spaced Neutron (DSN). Sidewall neutron tools are called Sidewall Epithermal Neutron Log (SWN) by Atlas Wireline, Sidewall Neutron Log (SNL) by Gearhart, Sidewall Neutron (SWN) by Welex and Halliburton, and Sidewall Neutron Log (SNP) by Schlumberger. Several other names have been used for other brands and types of conventional tools. Slimhole tools with one detector are called neutron-neutron or neutron tools; two-detector tools are called compensated neutron tools.

Several types of specialized neutron tools are also available, including pulsed neutron decay logs (neutron lifetime and thermal decay time logs) and neutron activation logs. Most of these are cased hole tools and have seldom been used in ground-water studies. Schlumberger (1989b) has a good discussion of these tools. Keys (1988) also discusses them.

Tool theory. Neutrons are electrically neutral particles with the mass of a hydrogen atom. Naturally occurring free neutrons are very rare in most formations. All neutron tools measure the response of a formation to bombardment from a neutron source in the tool.

High velocity, high energy (about 4 Mev) neutrons are emitted by a radioactive source in the tool. During the brief life span of a neutron (a few milliseconds), it passes through three energy levels that are of interest to neutron logging (Figure 4). As neutrons travel through the borehole and formation they undergo elastic collisions with nuclei, continuously changing direction and losing energy. The final stage of the slowing down process is an energy level called the **epithermal** state. As collisions continue, neutrons reach the **thermal** equilibrium energy state of atoms in the formations. While in the thermal state neutrons travel about, neither gaining nor losing energy. The final state is reached when a thermal neutron collides with a nucleus, resulting in the absorption of the neutron and the emission of a **capture gamma ray(s)**.

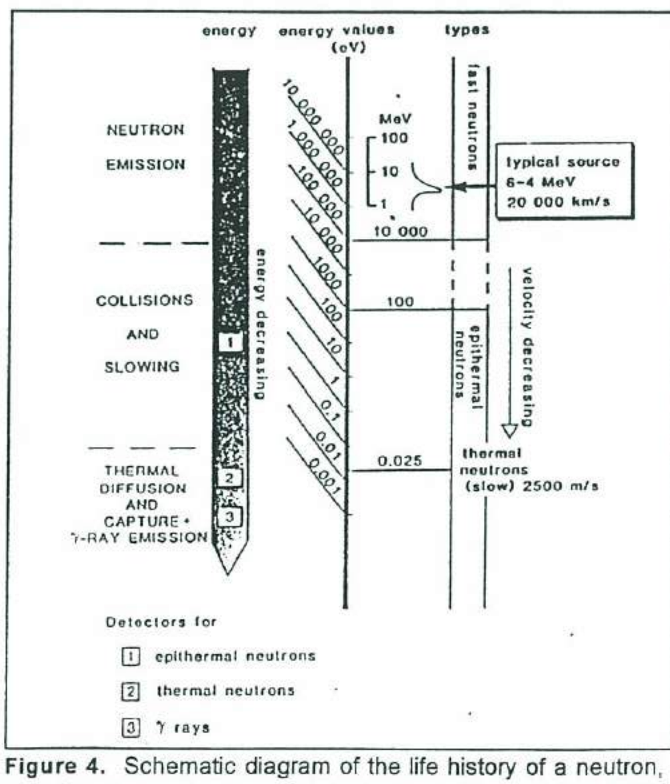


Figure 4. Schematic diagram of the life history of a neutron, showing energy levels and detector types (From Rider, 1986).

The ability of a nucleus to reduce the energy level of a neutron is measured in terms of its elastic interaction and thermal capture cross sections (Serra, 1984). Elastic interaction cross section is the ability of a nucleus to slow a neutron. It is a function of the size of the nucleus and the speed of the neutron. The closer the two particles are in size, the greater the amount of energy lost per collision and the greater the elastic interaction cross section. A hydrogen nucleus is approximately the same size as a neutron, giving it by far the highest elastic interaction cross section. The average energy loss per collision between neutrons and hydrogen is 50 percent (Serra, 1984), with neutrons reaching a thermal state after only 18 collisions. No other element commonly occurring in aquifer-quality rocks has anywhere near the elastic interaction cross section of hydrogen.

Thermal capture cross section is the ability of a nucleus to capture a neutron. The factors governing the thermal capture cross section of an element are not well understood. Elements with a high thermal capture cross section have a low elastic interaction cross section. Chlorine has one to two orders of magnitude higher thermal capture cross section values than any other element commonly occurring in aquifer-quality rocks. A few elements such as boron, cadmium, and gadolinium have extremely high cross sections, but these elements do not normally occur in sufficient concentrations in aquifer-quality rocks to affect neutron tool response. However, they are concentrated enough in some shales, igneous rocks, and metamorphic rocks to affect the neutron log.

A measurement of the neutron (or capture gamma ray) count rate by a detector located some distance from the source normally correlates to the hydrogen concentration of a formation. Since in most aquifer-quality rocks hydrogen only occurs in pore-filling fluids (water and hydrocarbons), the neutron count rate can be related to porosity.

Neutron tool design. All neutron tools utilize the same basic design, a neutron source and one or two detectors. Most tools employ a chemical source that is a mixture of beryllium and a radioisotope. The source provides a continuous emission of neutrons. Considerable variation exists in the type of detector(s) used. Detectors are available to measure epithermal neutrons, thermal neutrons, and capture gamma rays.

The count rate registered by all types of neutron detectors responds primarily to the hydrogen concentration of the formation. All detectors respond the same way to hydrogen: neutron count rate decreases as hydrogen concentration increases. However, all detectors do not respond the same to elements with high thermal capture cross sections (chlorine, boron, gadolinium, etc.). Epithermal count rates are not affected nearly as much as are thermal and capture gamma ray count rates. This difference in tool response is very important for proper neutron log interpretation.

Neutron tools which measure capture gamma rays have a count rate that is a function of both the thermal capture and the elastic interaction cross section. Consequently, these tools are very sensitive to changes in chlorine concentration (i.e. TDS) and trace element (boron, gadolinium, etc.) concentrations as well as changes in porosity. This makes calculating porosity very difficult (Bateman, 1985). Very few neutron tools today measure capture gamma rays.

Epithermal count rates are not significantly reduced by elements with high thermal capture cross sections. Epithermal count rate tools, therefore, are a more accurate means of determining porosity than are other types of neutron tools for rocks that contain shale, igneous rocks, and metamorphic rocks. This also means that, in general, the epithermal neutron tool has a smaller lithology effect than a thermal neutron tool. Epithermal tools are not suitable for cased holes, but can be used in air-filled holes. Since it is a pad device, the tool investigates only a portion of the borehole. Epithermal neutron tools, which date back to the 1950's, are not as common as are thermal neutron tools. Most epithermal tools are sidewall, but some are mandrel. They may or may not be compensated.

Thermal neutron tools are significantly affected by elements with high thermal capture cross sections. Porosity values will be too high when such elements are present. However, in complex lithologies mineral identification may be aided by the more pronounced lithology effects of the thermal tools (Etnyre, 1989). The tool can be run in liquid-filled, cased or uncased holes. It does not work very well in air-filled holes. All conventional thermal neutron tools are compensated. The tool should be run decentralized.

Depth of investigation and vertical resolution. The depth of investigation is a function of several factors including source strength, source-to-detector spacing, and hydrogen content of the formation and borehole. Depth of investigation increases as the source strength or the source-to-detector spacing increases. Tool design, therefore, must be taken into account when comparing the response of different neutron tools. The Compensated Neutron has approximately twice the depth of investigation. However, all other things being equal for a particular tool, hydrogen content is the chief factor controlling the depth. As hydrogen content increases, depth of investigation decreases.

Several factors determine hydrogen content (porosity, borehole rugosity, and mineralogy), but porosity is the chief control. As water-filled porosity increases, depth of investigation decreases from 24 inches to just a few inches. Formations with minerals that contain significant quantities of hydrogen or other elements with high thermal capture cross sections will also reduce the depth of investigation. In water-filled boreholes, rugosity and cavities increase hydrogen content and decrease depth of investigation, while in air-filled holes the depth of investigation is slightly increased for the same hole conditions.

Vertical resolution is a function of the source-to-detector or detector-to-detector spacing and the logging speed. As the spacing or the logging speed increases, the vertical resolution decreases. If the tool is stationary in the well bore, the vertical resolution equals the spacing (about 10 to 15 inches). At a logging speed of 30 feet per minute, the vertical resolution is 3 feet. Schlumberger has enhanced processing that, combined with a slower logging speed, improves the vertical resolution to 12 inches.

Log presentation. Neutron logs have a simple format. Modern conventional logs consist of only a porosity curve. A few slimhole logs present a porosity curve and some of them also include count rate curves. Most slimhole log presentations, however, consist solely of one or more count rate curves.

The porosity curve is usually placed across tracks 2 and 3. The values are expressed in decimal fractions. The scale depends on the range of anticipated porosity values. In sandstone provinces 0.6 to 0.0 is common. In mixed sandstone and carbonate provinces 0.45 to -0.15 is common when a density curve is included. The lithology on which the curve is calculated is noted on the log.

Count rate curves are usually placed in tracks 2 and 3. Count rates are usually expressed in counts per second.. However, old conventional logs used a number of other units of measurement including environmental units, API units, and standard units (Hilchie, l979).

DOWNHOLE VIDEO CAMERA

A wide variety of video cameras are available: color, black-and-white, directional capabilities, and rotating mirrors. Cameras are available to fit in 2" wells. They can be used to view fractures, cavities, bedding planes, etc. Cameras can be used in both open and cased holes, as long as the fluid is clear.

CALIPER

Caliper logs measure borehole diameter and shape. The tool is used to calculate borehole volume, make environmental corrections for borehole size and mudcake thickness, evaluate the condition of the borehole, identify porous and permeable zones, correlate, identify shale, select packer seats, and identify fractures and cavities. A variety of conventional and slimhole calipers is available. **Caliper** is the generic name for the tool.

Tool theory. The physical movement of one or more arms on a logging tool is converted to a borehole diameter by means of electrical circuitry. The arms are spring loaded so that they press against the borehole wall. Caliper tools vary widely in the number and types of arms which they employ.

The principal use of one-arm calipers is as an auxiliary measurement on certain pad-type tools (density and some neutron tools). One-arm calipers are standard on conventional pad-type tools, and many slimhole pad-type tools also have them. A one-arm caliper actually has two arms, the eccentering arm and the tool body, which is pressed against the borehole wall. True two-arm calipers are used on microresistivity and high frequency dielectric tools. Three-arm, four-arm, and calipers with more than four arms are also available. The caliper arms may be rod-shaped or bowsprings. Three-arm bowspring calipers are typically standard on conventional sonic tools and on some slimhole sonic tools where their primary function is to centralize the tool in the well bore. Four-arm calipers are found on dipmeters. Some calipers with four or more arms are stand-alone tools. Slimhole calipers are as good as conventional calipers.

The caliper tool has no depth of investigation. Vertical resolution depends on the design of the arms.

Log presentation. The caliper curve is usually placed in track 1 on conventional logs. It is scaled in inches. A line representing bit size is sometimes added to track 1. Slimhole caliper curves may be presented in any column.

Calipers with four or more arms typically will have at least two caliper curves. They may be presented as a separate log with the calipers plotted in tracks 2 and 3.

Interpretation. Borehole enlargements are due to fractures, cavities, soluble rocks (e.g. salt and gypsum), and unconsolidated rocks that disintegrate and cave (Figure 9). Fractures usually occur in carbonates, igneous, and metamorphic rocks. Cavities occur in carbonates. In Tertiary age formations unconsolidated rocks may be shale, sand, or gravel. In Mesozoic and Paleozoic rocks usually only the shales wash out.

A hole diameter less than bit size is due either to swelling, sloughing shale or to mudcake buildup on permeable formations. Most of the time it will be due to mudcake. A hole diameter equal to bit size (an in-gauge hole) will be in a low permeability, unconsolidated formation (Figure 9).

Calipers vary considerably in their resolution due to differences in the amount of contact area on the arm (rod or bowspring), the number of arms, and the pressure exerted by the arms. Bowspring calipers are less sensitive. Calipers with small arms or high pressure may cut through the mudcake, while others ride on the mudcake.

Many boreholes are noncylindrical. Figure 10 illustrates how different types of calipers theoretically behave in such holes. However, remember that there is no way to be sure that each caliper tool is tracking the borehole as described in the following discussions. One and two-arm calipers both tend to measure the long axis. However, they each contact the borehole wall and sense changes in diameter differently (Jorden and Campbell, 1984). Three-arm calipers generally measure only one diameter -- something in between the maximum and minimum diameters. Four-armcalipers (sometimes called X-Y calipers) display two perpendicular measurements, generally the minimum and maximum diameters. Thus each type of caliper gives a different picture of the well bore.

Rod-type arms such as those on one-arm calipers have small contact areas and therefore generally slice through mudcake. However, the vertical resolution of the one-arm caliper is better than that of the two-arm which has a larger arm. Pad-type arms used on microresistivity tools tend to ride on the mudcake. Bowspring arms may or may not cut through the mudcake, depending on the pressure and width of the spring. One-arm calipers are usually found on density and neutron tools which have a leading edge on the sonde that cuts through the mudcake. Only the backup arm of the tool is measuring mudcake. Thus, theoretically, the caliper measures only one-half the mudcake thickness.

An additional complication is the fact that the same caliper tool will not repeat perfectly on multiple runs. The tool will not always measure the same part of the well bore on each pass.

Fracture detection. In order to detect fractures with a caliper, the fractures must be open or enlarged at the wellbore to a width sufficient to be detected by the particular caliper. Very sensitive calipers are available, resolving changes in borehole diameter as small as 1 mm, but the changes may or may not correlate to fractures. Fractured zones that cave into the well bore are also detectable. Vertical fractures may not be detected or they may appear as separate anomalies at different depths (Howard, 1990). Elliptical boreholes may indicate fracturing. Depending on the drilling method, fractures may have mudcake and the hole diameter may be bit size or less. Some fractures, horizontal and vertical, cannot be detected with a caliper.

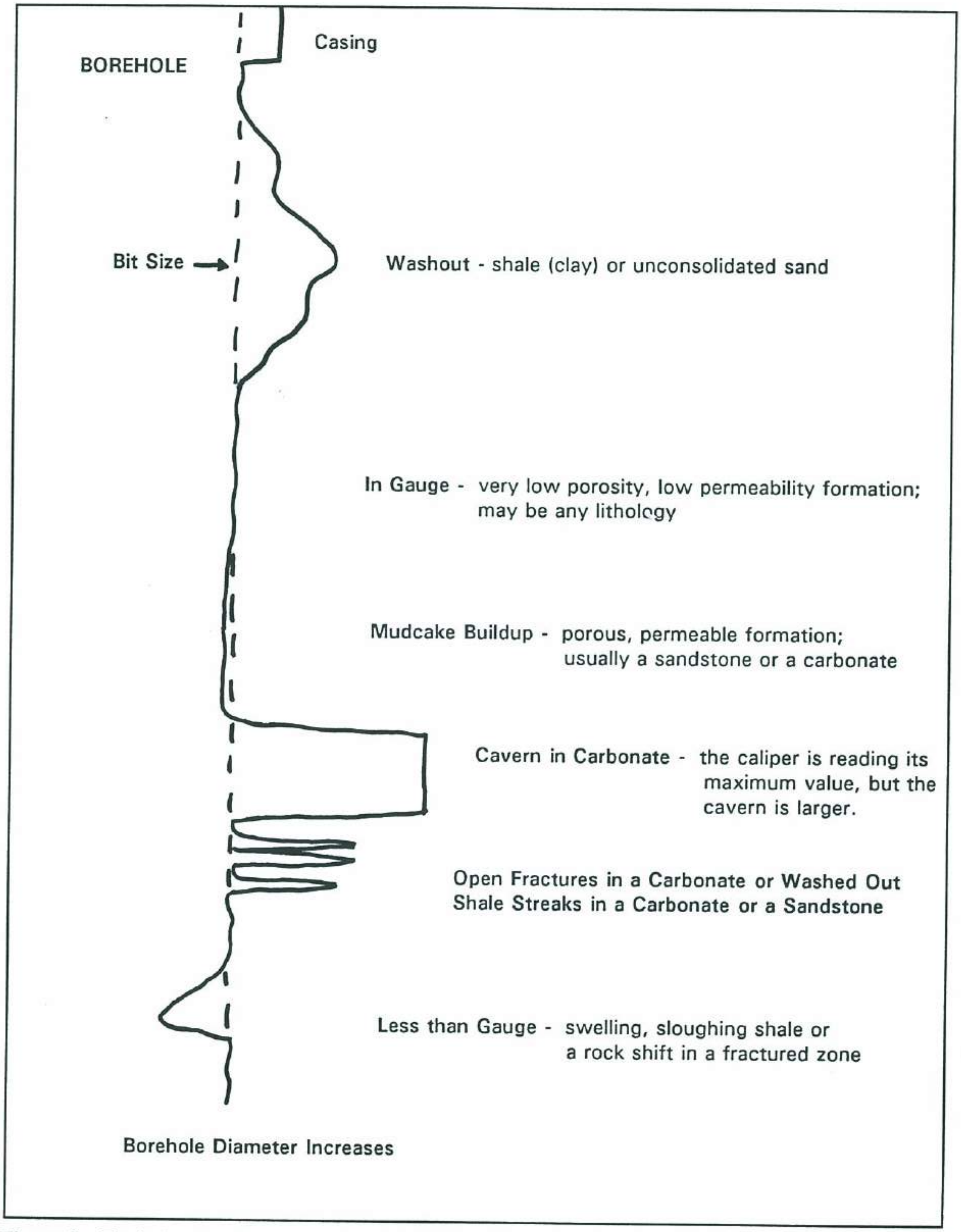


Figure 9. Typical caliper log responses.

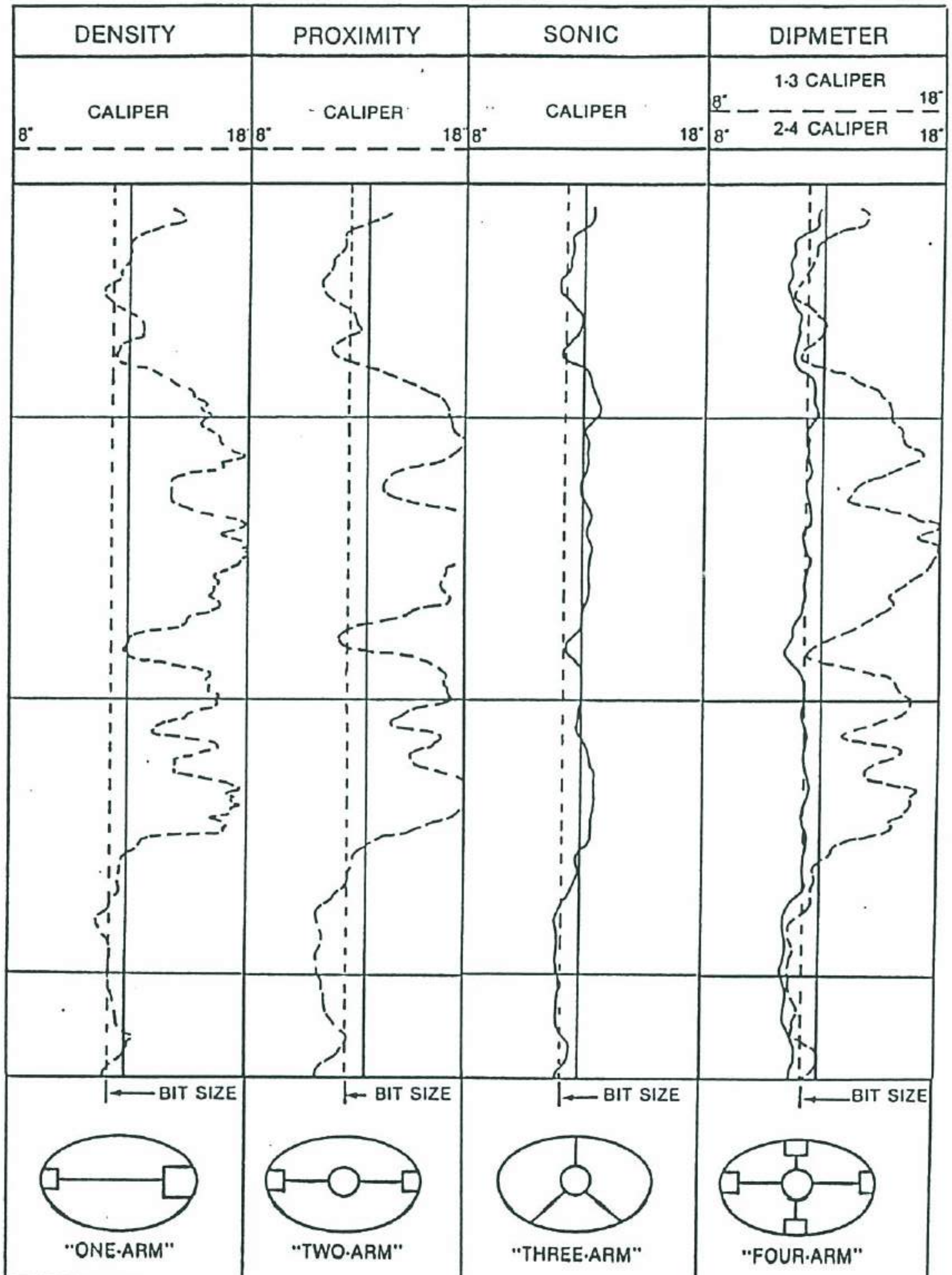


Figure 10. Comparison of the response of different types of calipers in the same noncylindrical borehole (From Jorden and Campbell, 1984).

DENSITY (GAMMA-GAMMA)

The density or gamma-gamma tool is an excellent porosity tool. It is also used to pick bed boundaries. In conjunction with other porosity tools it can be used to determine lithology. It is used in conjunction with the sonic log to calculate acoustic impedance for synthetic seismic traces and to calculate formation mechanical properties such as Poisson's ratio and Young's modulus. While it is predominately an openhole tool, research is being conducted into methods of obtaining quantitative data through metallic casing (Jacobson and Fu, 1990). Density tools are used to detect voids in gravel packs in cased holes. Attempts have been made to evaluate the distribution of bentonite grout behind PVC casing utilizing slimhole density tools (Yearsley, et al., 1991).

In some parts of the country the tool cannot be run in openhole water wells. The concern is that the radioactive source would create very localized radioactive contamination if the tool should become stuck in the borehole.

The most common name for modern conventional tools is Compensated Density (CDL). Atlas Wireline uses the name Compensated Densilog (CDL); Schlumberger calls its tool the Compensated Formation Density (FDC). Slimhole tools are called either density or gamma-gamma and the term compensated is added when appropriate.

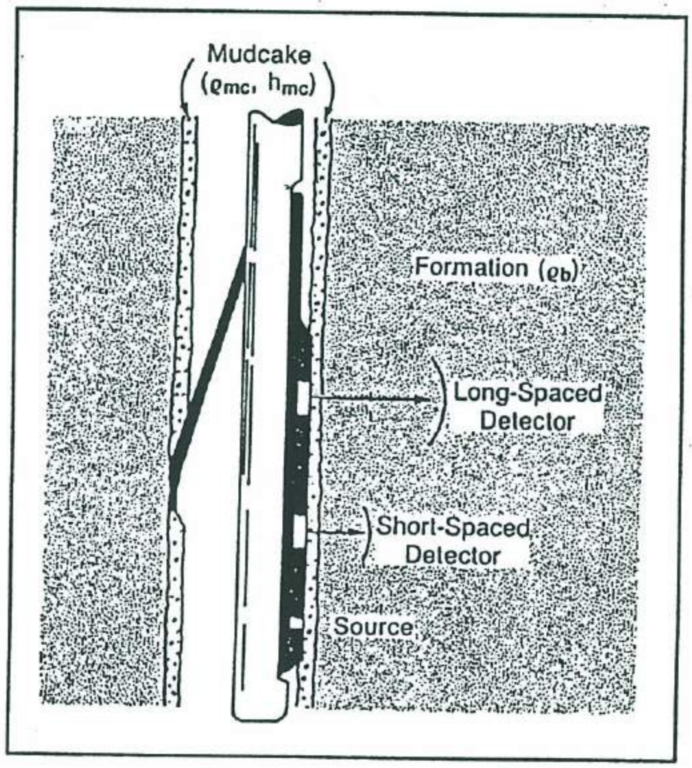


Figure 17. Schematic drawing of a compensated density tool (From Schlumberger, 1989, modified from Wahl, et al., 1964).

Tool theory. Conventional and some slimhole density tools utilize a source which emits medium-energy gamma rays (Cobalt 60 or Cesium 137) and which is mounted in a shielded sidewall skid. The skid is pressed against the borehole wall by means of an eccentering arm that also functions as a caliper (Figure 17). The pressure of the eccentering arm, plus the plow-shaped design of the leading edge of the skid, usually allows the skid to cut through the mudcake.

The tool design creates collimated (focused) gamma rays that pass into the formation. As the gamma rays pass through the formation several reactions take place. Compton scattering is the only reaction of consequence to most density tools. It occurs when gamma rays lose energy and change direction due to collisions with electrons in the rock and fluid.

Density tools measure the attenuation of gamma rays between the source and one or two detectors. The detectors emit an electrical pulse for each gamma ray that is intercepted. The count rate varies by a factor of 5 to 10 for common sedimentary rocks (Dewan, 1983). The detectors are shielded in such a way that they respond only to the gamma rays undergoing Compton scattering. Such shielding makes the count rate a function of the electron density.

The gamma ray count measured by the detector(s) is inversely proportional to the electron density (ϱ_e) of the formation. Electron density, in turn, is proportional to the bulk density (ϱ_b) of the formation. For common sedimentary rocks the ratio of ϱ_e to ϱ_b varies very little. This means that it is a relatively easy, accurate, and straightforward process to convert the gamma ray count to bulk density. Conventional and some slimhole density tools output bulk density as the "raw" data curve.

There is considerable variation in the design of slimhole density tools. Some tools are compensated (dual detectors), but many are single detector. The single detector tools include omnidirectional, mandrel tools as well as sidewall tools. Omnidirectional density tools are commonly called 4-pi density tools. The name alludes to the fact that the tool investigates a spherical area, the volume of which is $4\Pi r^3/3$. The Greek letter Π is pi. The tool may or may not be centralized. Uses include gravel pack evaluation and delineation of thin beds in coal sequences (personal communication, Lynn Gray Breaux, 1991).

Depth of investigation and vertical resolution. Depth of investigation is only a few inches, with 5 inches a good average value.

This shallow depth of investigation makes the tool response very susceptible to the influence of borehole conditions such as excessive hole rugosity and thick mudcake. Porosity values are too high when such conditions exist. Drilling methods (such as augering) that disturb the formation for just a few inches away from the well bore will adversely affect the ability of the tool to measure true bulk density.

Vertical resolution of conventional tools is about 3 feet at average logging speeds (30 feet per minute). Slowing the logging speed to about 15 feet per minute improves the statistics, thus increasing the vertical resolution to 1.5 feet. Petroleum logging companies offer high resolution density logs with a vertical resolution of 0.5 feet. The improved resolution of this tool is accomplished by combining a slower logging speed and an increased sampling rate with a different processing technique.

Vertical resolution is also a function of the source-to-detector(s) or the detector-to-detector spacing. The smaller the spacing the better the vertical resolution. While the spacing varies somewhat for each brand of density tool, average values are 16 inches for single detector conventional tools and 10 inches between detectors for compensated conventional tools (Serra, 1984). Slimhole tools usually have spacings that are a few inches smaller. Good vertical resolution makes the density log useful for determining bed boundaries.

Log presentation. Density logs vary considerably in their presentation. They may consist of one to seven curves, but the common format is five curves: bulk density, porosity, correction, caliper, and tension.

Conventional and some slimhole density tools record bulk density as the "raw" data curve (Figure 18), but some logs include count rate curves. The bulk density curve is labeled RHOB on the header, which is computer keyboard phonetics for ϱ_b. The unit of measurement is grams per cubic centimeter (g/cm^3). The curve is usually placed across tracks 2 and 3 with a linear scale of 2.0 g/cm^3 to 3.0 g/cm^3. This scale covers the range of values occurring in common sedimentary rocks with less than 46 percent porosity.

The output of many slimhole tools is simply the count rate of each detector scaled in counts per second. For many of these logs no further processing is or can be done to the data. Compensated density tools correct the bulk density curve for the presence of mudcake not removed by the leading edge of the sonde and for washouts and borehole rugosity by comparing the differences in the count rates of the two detectors by means of an experimentally derived "spine-and-ribs" plot. The correction is automatically added to the bulk density curve, making it in actuality a corrected bulk density curve. The amount of correction is documented on the log as a separate curve labeled $\Delta\varrho$ **(DRHO)**. The

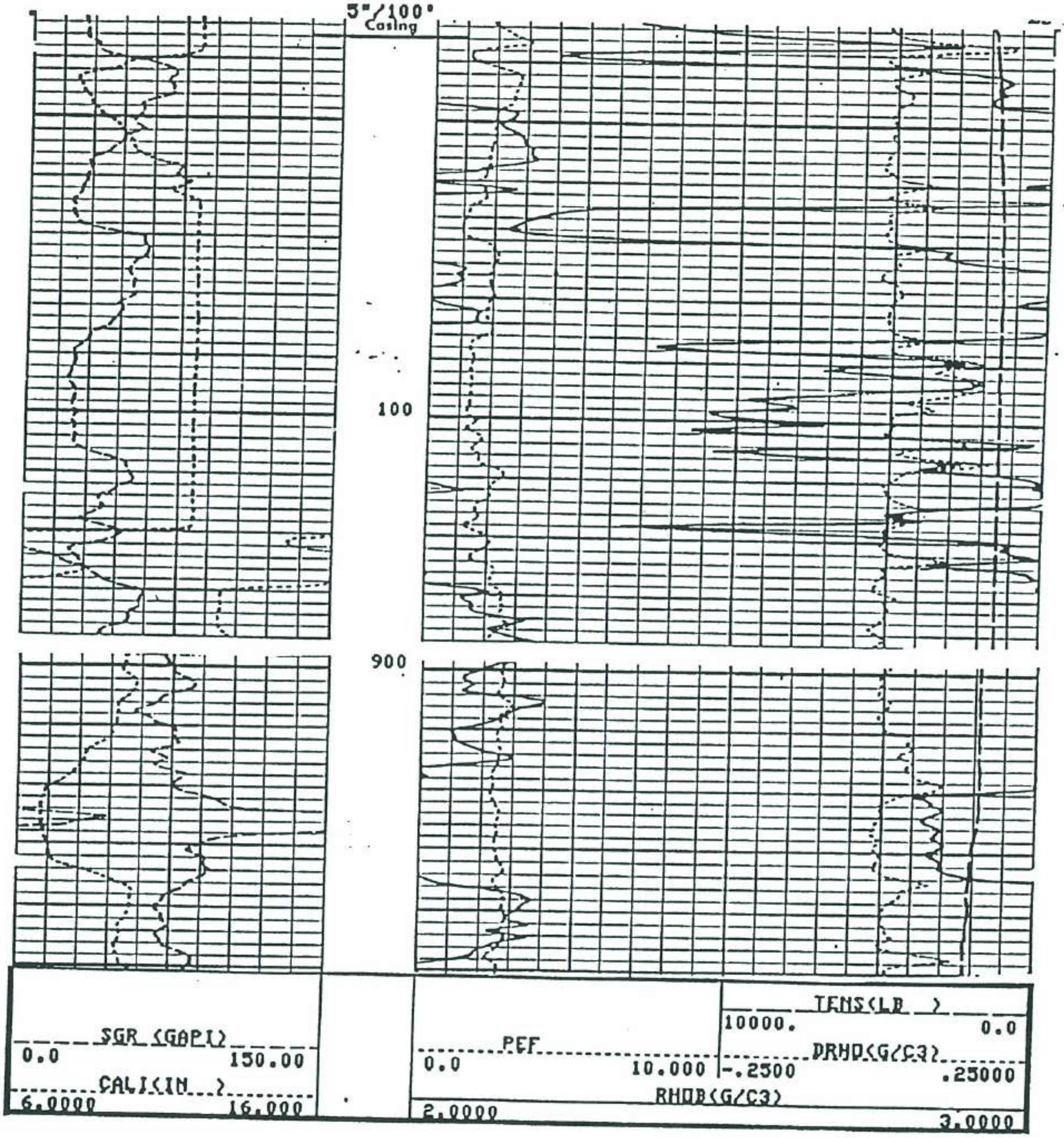


Figure 18. Typical format for a conventional compensated density log. (The example is actually a lithologic density log). Track 1 contains total gamma ray (SGR) and caliper curves. Track 2 contains a photoelectric factor (PEF) curve which is only found on a lithologic density log. As is standard practice, the unit of measurement of the PEF curve is not noted. Track 3 contains the tension (TENS) and $\Delta\varrho$ (DRHO) curves. The ϱ_b curve plots across tracks 2 and 3. In the large washout from 64 to 120 feet the ϱ_b curve is predomionately reading the bulk density of the mud. The washout is so large that the $\Delta\varrho$ curve makes no correction.

curve is usually placed in track 3 with a scale of -0.25 g/cm^3 to 0.25 g/cm3.

A caliper curve is standard on most density logs. The backup arm of the sonde makes the caliper measurement. The curve is usually placed in track 1. It serves as another good quality-control indicator of the bulk density curve.

A porosity curve, if included, is usually placed in tracks 2 and 3. The values are expressed as decimal fractions. The curve is variously scaled. In sandstone provinces 0.6 to 0.0 is common. In boreholes with both sandstones and carbonates 0.45 to -0.15 is common. The lithology on which the curve is calculated is noted on the log.

Fractures. Fractures can create sharp reductions in bulk density values and a corresponding peak on the $\Delta\varrho$ curve. The effect may be so slight as to almost disappear after time-constant averaging of petroleum-type tools. Better fracture detection requires a smaller time constant, but this is at the expense of the general quality of the density log (Suau and Gartner, 1980). In an elliptical borehole, the tool will track in the major axis. Remember that washouts and vugs can cause the same response.

SONIC (ACOUSTIC)

The sonic tool is used to calculate porosity, pick bed boundaries, and identify abnormally pressured formations. In conjunction with another porosity tool, it can be used to determine lithology. In conjunction with the density tool it is used to create synthetic seismograms and to calculate rock mechanical properties such as Poisson's ratio and Young's modulus.

Specialized sonic tools have been developed to identify fractures (Variable Density Log), evaluate cement bond quality (Cement Bond Log), and image the borehole (Borehole Televiewer). Research is presently underway to develop methods to calculate permeability from sonic tools. Efforts are underway to develop accurate cased hole sonic porosity tools, but presently the tool works much better in open holes. Normal sonic tools only operate in liquid-filled holes.

The sonic was the first porosity tool. Popular in the 1950's, it has been supplanted in oilfield logging by the density-neutron combination. In groundwater/environmental investigations, however, it is more widely utilized. This is probably due in large part to the ease and safety (no radioactive source) with which it can be operated.

Modern conventional tools carry a variety of names: Borehole Compensated Acoustic (AC) for Atlas Wireline, Borehole Compensated Sonic (BCS) for Gearhart, Compensated Acoustic Velocity (CAV) for Welex and Halliburton, and Borehole Compensated Sonic Log (BHC) for Schlumberger. Each company also has a Long Spaced Sonic and a Full Wave Sonic, as well as various other specialized sonic tools. Slimhole sonic tools are available and a few are compensated. Slimhole full wave sonic tools are also available.

Tool theory. Ordinary sonic tools utilize a transmitter(s) and receivers to measure the velocity of sound in a formation. The transmitter generates, 10 to 60 times a second, a high frequency (20 to 40 kilohertz) sound wave that travels out in all directions through the tool, borehole fluid, and formation. This sound wave actually consists of several different types of waves: compression (P, pressure, or longitudinal), shear (S or transverse), Rayleigh, and Stonely. Under normal conditions, the first component of the wave to arrive at a receiver is that part of the compression wave which struck the borehole wall at the critical angle and traveled vertically through the formation (Figure 19). This is the only wave of interest to ordinary sonic tools and it is the wave used to calculate porosity. Other sonic tools record the amplitude, attenuation, travel time, and/or frequency of the various components of the wave train.

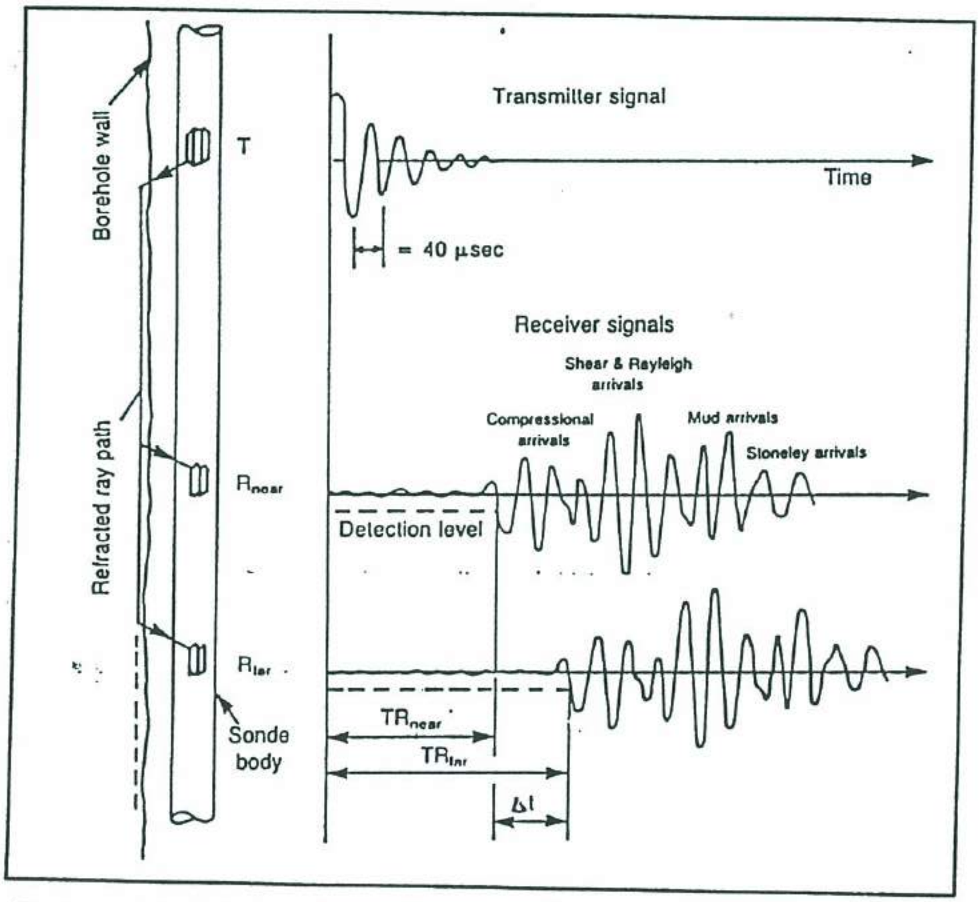


Figure 19. Basic sonic tool design, along with an acoustic wavetrain. The compression wave activates the receivers (Modified from Dewan, 1983).

The sonic tool measures the time it takes a sound wave to travel from the transmitter to each receiver. The difference between the two values, divided by the receiver spacing, is the time it takes for the compression wave to travel 1 foot in the formation. This calculation assumes that the distance from the borehole wall to each receiver is the same. The only way to be assured of this is to compensate the tool.

Tool design. Modern conventional tools and some slimhole tools are compensated. The standard design used to be a double array of one transmitter and two receivers inverted to each other. Averaging the two measurements factors out errors in calculating sonic velocity due to washouts and tilted tools. Today some sonic tools are compensated by other methods, but the result is the same. In severe washouts compensated sonic measurements are less affected than are other porosity tools.

Most modern tools use piezoelectric ceramic crystals as the transmitting transducers. Electric current is used to physically deform the crystal, thus producing a sound wave. The receivers are also transducers, except in this case they convert acoustic energy to electrical energy.

Typically the distance between the transmitter and the near receiver is 3 feet, but it can be up to 10 feet. The distance between the two receivers is normally 2 feet, but spacings of 1 to 3 feet are used. The tool is constructed in such a way as to attenuate the sound wave traveling the length of the tool. Slots in the steel housing or a rubber insert in the housing are commonly used to accomplish this.

Sonic tools perform best when centralized in the borehole. One of the centralizers is also utilized as a caliper. The centralizers are normally bow springs, which means that the caliper measurement is not very sensitive.

Depth of investigation and vertical resolution. Vertical resolution is the distance between the two receivers (normally 2 feet). Beds thinner than this distance are detected by the tool, but the log values will not be accurate and may trend in the opposite direction of the actual travel time.

Travel time measurements are not affected by formations outside the detector spacings (Etnyre, 1989). The sonic tool is the only porosity tool with this characteristic. This contributes to its excellent vertical resolution, which is better than any other porosity tool.

Depth of investigation ranges from 5 to 40 inches into the formation (Serra, 1984). Most of the time the actual depth is from 8 to 12 inches (Hilchie, 1982). Depth of investigation is predominately a function of wavelength which, in turn, is a function of velocity and frequency.
The longer the wavelength the deeper the penetration. In formations (normally shales) that have altered zones next to the borehole, the depth of investigation can be increased beyond the altered zone by using a long spaced sonic tool. This is necessary only if the sonic log is to be incorporated into a seismic study.

Log presentation. Sonic logs are a recording versus depth of the time it takes a sonic wave to travel 1 vertical foot of formation. The measurements are called **interval transit time**, **interval travel time**, **transit time**, **travel time**, **Δt (delta t)**, or **t**. The unit of measurement is microseconds (μs or μsec) per foot. Using microseconds rather than seconds makes the values whole numbers.
Δt is the reciprocal of velocity in feet per second. The relationship between the two is expressed by the following equation:

$$\Delta t = \frac{10^6}{velocity} \quad (1)$$

Interval transit time is normally presented across tracks 2 and 3. Transit time increases to the left, which means that porosity also increases to the left. The scale is linear and normally is either 140 to 40 μsec/ft or 150 to 50 μsec/ft.

Fractures. Sonic logs have been used for a number of years to detect fractures. A variety of techniques have been developed, from simply looking for cycle skips to anaylsis of the full waveform. As with all routine logs, however, a plethora of other conditions can produce the same acoustic respone as a fracture. Bad borehole conditions, vugs, unconsolidated and uncompacted formations, and soft shale beds can also disrupt the wavetrain, thus the need for additional logs such as the caliper and the gamma ray. Also, steeply dipping fractures may not attenuate the wavetrain.

Cylce skipping has long been used to indicate fractures (Figure 20). Cycle skipping is a sharp increase in travel time, usually in increments of 5-7, 10-14, or 20-25 μsec/ft, (depending on the tool design) caused by attenuation of the acoustic signal from the near to the far receiver (Hilchie, 1987). It occurs opposite horizontal fractures. Cycle skipping is much rarer on modern petroleum sonic logs because the systems have noise rejection logics in the measurement systems that eliminate cycle skipping (Hilchie, 1987). Slimhole sonic logs are not as sophisticated.

Full waveform techniques involve analysis of the shear and Stoneley components of the acoustic wavetrain. These waves arrive after the compression wave and are significantly attenuated by fractures. Older techniques consisted of plotting the wavetrains, either as time-amplitude traces or as variable intensity plots, and looking for disruptions in the patterns (a "Chevron" pattern or a sudden break in the pattern of the waveform). Variable intensity plots, also known as Variable Density Logs (VDL), depict the amplitudes of the wavetrain as black and white strips. The VDL tool employs a single transmitter and a single receiver.

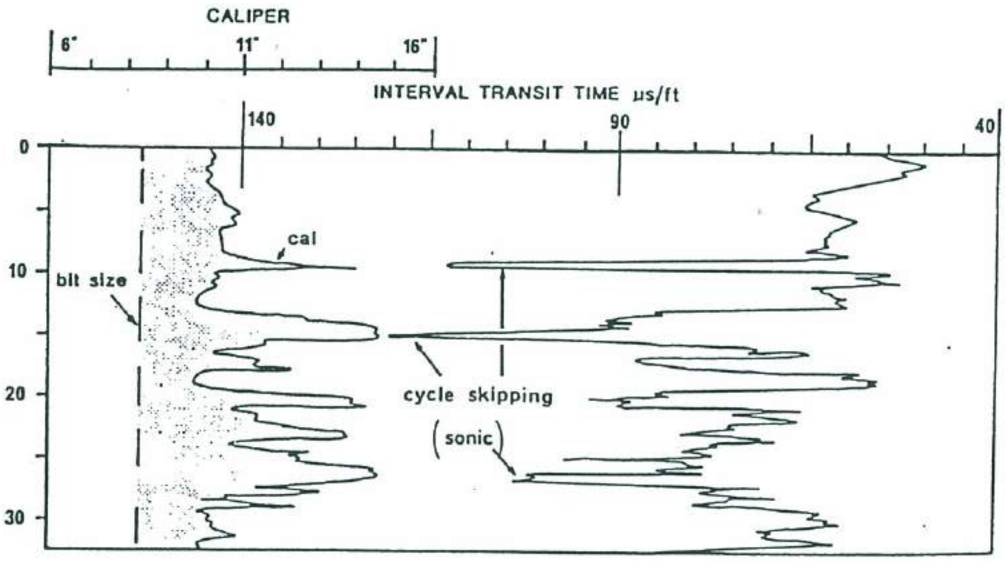
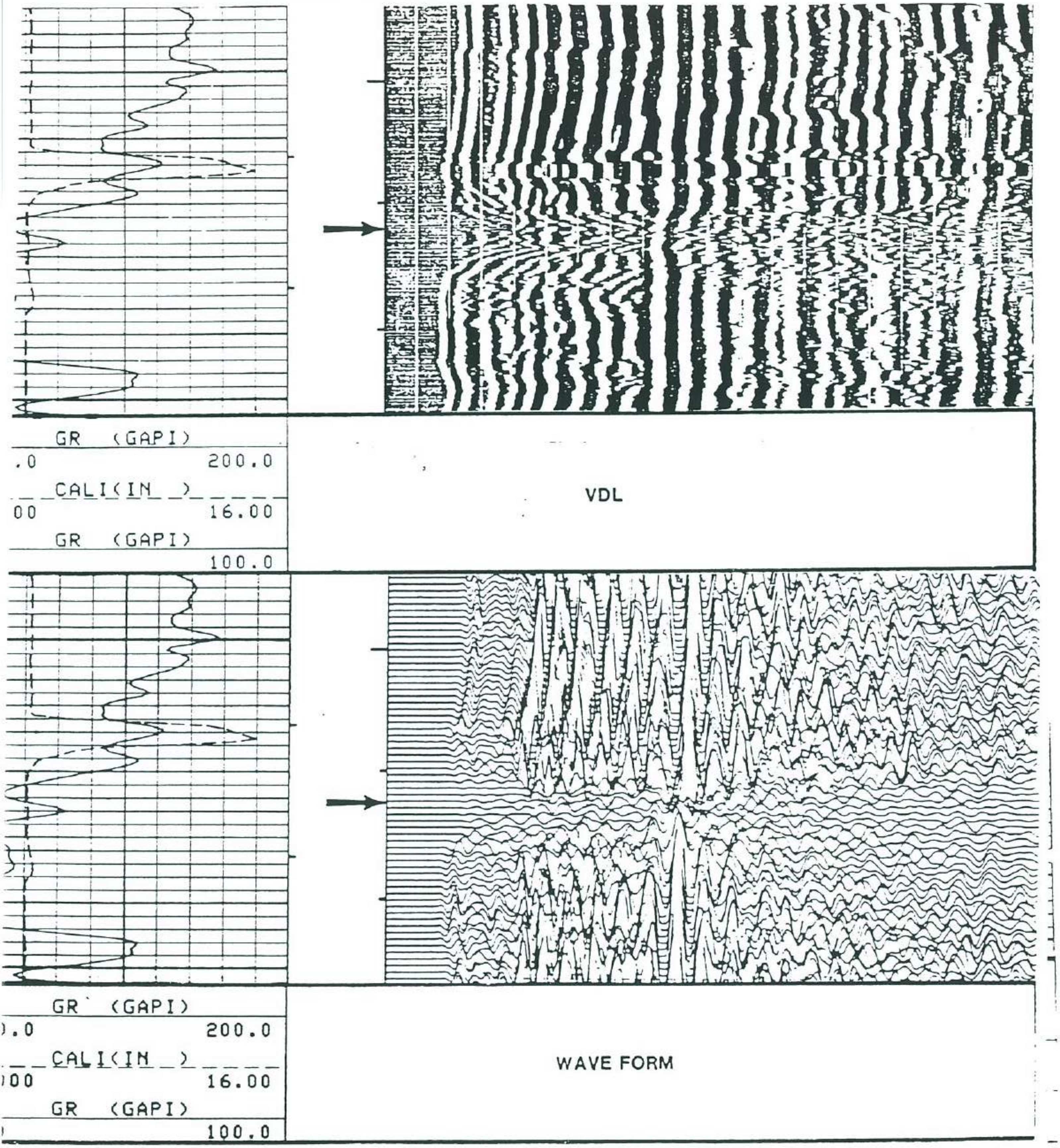


Figure 20. Cycle skipping on acoutic logs caused by fracturing (Howard, 1990, after Rider, 1986)

VARIABLE DENSITY-WAVEFORM LOG



(McGinley, 1986)

TEMPERATURE

Temperature tools measure both gradient, the actual temperature of the borehole fluid, and differential temperature, relative changes in fluid temperature. The differential curve is more sensitive to both fluid migration in the borehole and variable thermal conductivity. It can be an excellent fracture detection tool.

In the absence of fracture flow, the vertical temperature gradient will be a smooth line corresponding to the local geothermal gradient and the differential temperature log will be a straight line. Fluid flow produces a number of responses, but they do not always occur on the log.

It is best to run the tool after the borehole fluid has equilibrated to natural temperatures and flow conditions. This may take days to months in static monitoring wells. Flowing wells will equilibrate rapidly. The temperature tool should be the first log run and it should be run going downhole.

FLOWMETER

There are three types of flowmeters: impeller or spinner, heat-pulse, and electromagnetic. With the impeller flowmeter measurements can be made continuously or at discrete depths. Heat-pulse and electromagnetic measurements are made at discrete depths.

The impeller flowmeter was developed in the 1920's (Howard 1990). As the impeller spins, due to water flow and movement of the tool in the borehole, a sensor records the revolutions of the blade. This information is then converted to flow rate. Logging speed must be subtracted from the log response to accurately calculate the flow rate. For low flow rates, impeller flowmeters must be run very slowly using a large blade. A flow of at least 2 m/min is required to turn sensitive impellers (Howard, 1990), but Century claims that their flowmeter has been tested to a logging rate of 2 feet/minute with a 4" blade (Peterson, n.d.). Impeller flowmeters require frequent maintenance and calibration (Molz and Young, 1993).

The heat-pulse and electromagnetic flowmeters are recommended for low flow rates. Hess (1986) reported on a heat-pulse flowmeter that can resolve flows of 0.01 m/min with a normal range of 0.06 to 6 m/min.

The Tennessee Valley Authority Engineering Laboratory has recently developed an electromagnetic flowmeter. It has no mechanical parts and is in the shape of a hollow cylinder with an electromagnet and two electrodes in the walls (Moltz and Young, 1993). The instrument operates according to Faraday's law of induction to produce a voltage that is proportional to the velocity of the water passing through the central cylindrical channel. It has a threshold velocity of less than 0.088 m ± 0.009 m/min (Moltz and Young, 1993).

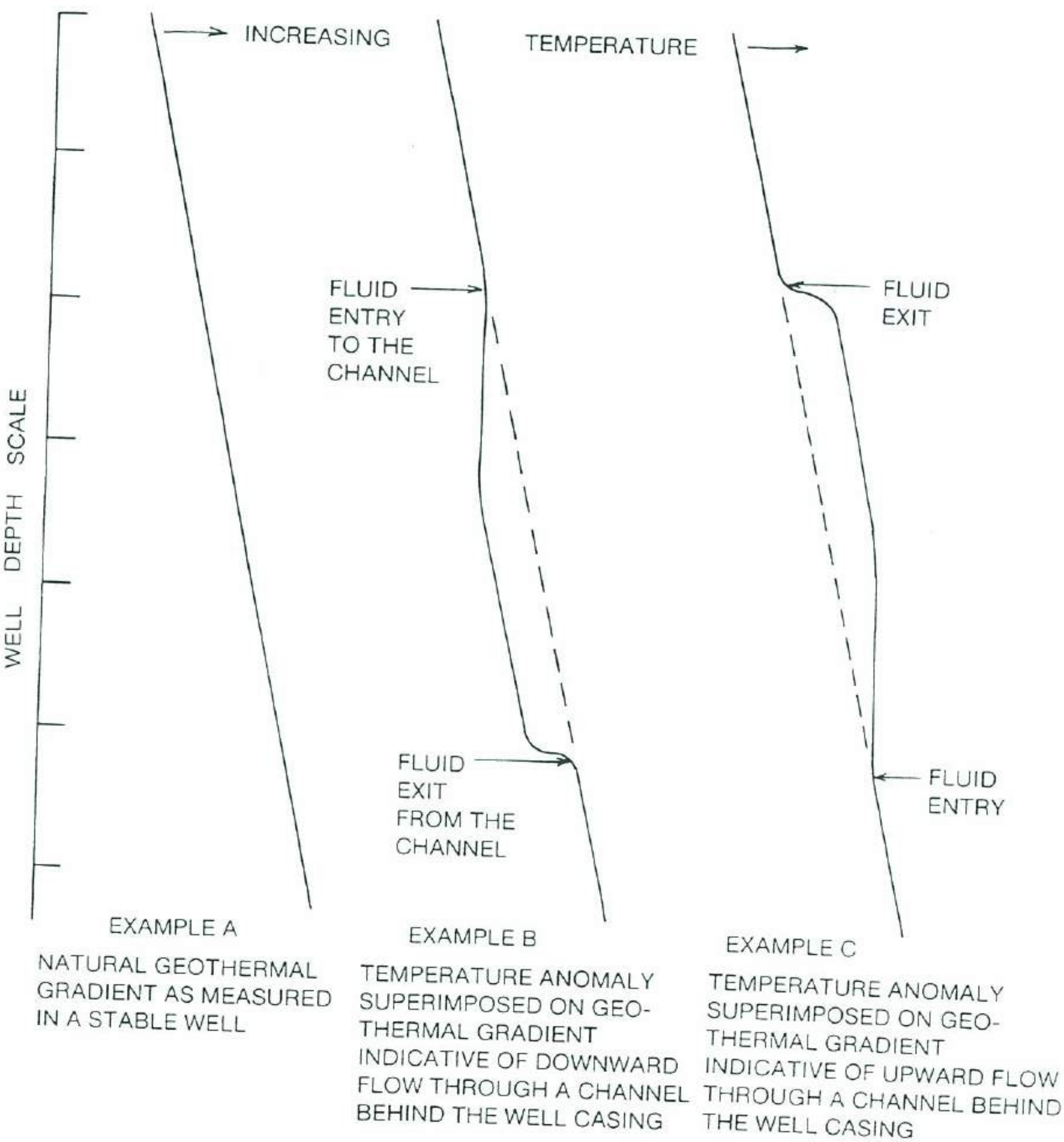


Figure 19. Examples of gradient temperature logs showing the natural geothermal gradient and anomalies caused by flow through a channel behind the well casing.

Nielsen & Aller (1984)

Hughbert Collier's professional experience includes 20 years of consulting, research, and teaching throughout the United States. He taught geology at Abilene Christian University and Tarleton State University prior to starting Collier Consulting. Collier Consulting provides a wide range of geological services to petroleum and environmental clients. Recent consulting work has included construction and analysis of petroleum and groundwater databases for field studies, editing of digital log databases, petrophysical analysis for DOE and GRI funded research projects, and reservoir characterization studies. Hughbert specializes in reservoir characterization by integration of logs, cores, and cuttings.

Hughbert has authored a dozen papers, including a textbook, **Borehole Geophysical Techniques for Determining the Water Quality and Reservoir Parameters of Fresh and Saline Water Aquifers in Texas**. After receiving B.S. and M.A.T. degrees in geology from Mississippi State University, Hughbert completed a Ph.D. in Geosciences from the University of Texas at Dallas. Professional associations include SPWLA, AAPG, and NGWA.